The Role of Relational Agents in Regional Economic Evolution and Resilience: The Case of Robotics Systems Integrators

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Benjamin R. Kraft

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The Role of Relational Agents in Regional Economic Evolution and Resilience: The Case of Robotics Systems Integrators

Approved by:

Dr. Nancey Green Leigh, Advisor
School of City and Regional Planning
College of Design
Georgia Institute of Technology

Dr. Kaye Husbands Fealing
School of Public Policy
Ivan Allen College of Liberal Arts
Georgia Institute of Technology

Dr. Stuart Andreason
Center for Workforce and Economic Opportunity
Federal Reserve Bank of Atlanta

Dr. Jan Youtie
School of Public Policy
Ivan Allen College of Liberal Arts
Georgia Institute of Technology

Dr. Subhrajit Guhathakurta
School of City and Regional Planning
College of Design
Georgia Institute of Technology

Date Approved:

March 2, 2020

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For better and worse, doctoral study and dissertation writing is not confined to the campus. My parents, Joe and Susan Kraft, could easily have refused any type of support as their son accumulated academic degrees in lieu of professional experience (and paychecks), but instead they stood by with approval, interest, and the all-important occasional financial support that most PhD students find themselves needing at various points throughout the process.

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LIST OF SYMBOLS AND ABBREVIATIONS

BLS	Bureau of Labor Statistics
EEG	Evolutionary Economic Geography
ENC	East North Central Census Division
EOAT	End of Arm Tool(ing)
IFR	International Federation of Robotics
KIBS (t-KIBS & b-KIBS)	Knowledge Intensive Business Services (technology-KIBS & business-KIBS)
KSAO	Knowledge, Skills, Abilities, and Other Characteristics
MaHC	Macro approaches to Human Capital
MiHC	Micro approaches to Human Capital
RIA	Robotics Industries Association

SUMMARY

This dissertation addresses the question of how legacy industrial regions—those that have historically relied on manufacturing (and to an extent also resource extraction and agriculture)—can regain or sustain competitiveness in a global, service-dominant, and digitally automated economy. This question is examined through the lens of a small industry that is geographically concentrated in these regions and provides services directly related to material production.

The industry is called robotics systems integration. It consists of engineering consultants and service providers that design and implement robotic automation systems for manufacturers.

The conceptual framework underlying this inquiry is that of evolutionary economic geography (EEG), which views economic evolution as in some ways analogous to biological evolution. From this perspective, the role of firms is similar to the role of biological organisms, because both firms and organisms scale up to form ecosystems, and these ecosystems can be studied at a regional level. Understanding how these ecosystems work can help to understand why some regions and industries stagnate and decline, and what can be done to change these trajectories of these regions. Special attention is given to the role of individual and organizational agency in transferring the information needed for regional economic ecosystems to adapt.

Data was collected through a survey and interviews of robotics systems integrators. The analysis in the dissertation is organized around four main themes. They are: integrators' geography, their role and position in the robotics supply chain, their

ability to absorb and propagate a type of evolutionary information called related variety, and their human capital needs and practices.

Results suggest that integrators are indeed agents for facilitating the evolutionary transfer of information within and between regional industrial ecosystems, and across multiple technologies. Key pathways for this transfer are 1) interactions with customers and suppliers, and 2) human capital practices that prioritize a "synthetic" sensibility over a codified set of skills. This synthetic sensibility is characterized by a predilection towards solving practical physical, material, and spatial problems of the kind often presented when working with industrial automation systems.

These evolutionary information transfers are geographically contingent. While integrators' customers are geographically dispersed, integrators themselves are heavily concentrated in legacy industrial regions, and this pattern does not appear to be changing any time soon. Moreover, integrators actively recruit for personnel from nearby institutions and prioritize these synthetic sensibilities that are embedded in legacy regions during recruitment.

While this research cannot establish a direct causal link between robotics systems integrators and the evolutionary trajectory of their regional industrial ecosystems, it does suggest that further probing these issues by looking at similar regions and industries could be helpful in identifying productive evolutionary paths forward for peripheral regions often thought to be left out of the 21st century knowledge- and service-based economy.

CHAPTER 1

INTRODUCTION AND PROBLEM STATEMENT

1.1 Problem Statement and Research Approach

This dissertation addresses the problem of preserving and restoring economic competitiveness in declining legacy industrial regions of developed nations. The term "legacy industrial region," refers to a subnational geographic region that has continued to rely disproportionately—relative to other regions—on manufacturing or extractive activities to sustain its economy throughout the second half of the 20th century and into the 21st century.

As economic polarization increases, there is growing recognition that second-tier formerly industrial cities, unable to compete in the same technology, media, and financial arenas as first-tier Global cities (and their regions), will be left behind (Badger, 2017). However, a strain of economic development and economic geography literature has critiqued this perspective as economically and technologically determinist, arguing that regions' developmental destinies are not predicted wholly by their industrial specializations, and that regions and firms within them have agency in shaping their economic futures (Christopherson & Clark, 2007; Clark, 2013; Lowe & Wolf-Powers, 2017; Truffer & Coenen, 2012). In the wake of the Great Recession, this voice has gotten louder and begun to focus more attention on the spaces in which deindustrializing regions *can* compete in a global, knowledge- and service-based economy. Often, these spaces are updated versions of once-dominant manufacturing specialties and the services related to them. Two issues of the *Cambridge Journal of Regions, Economy, and Society* on regional resilience (Volume 3, Issue 1, March 2010) and reindustrializing regions (Volume 7, Issue 1, March 2014) are emblematic of this focus. The articles in these issues, and others like them, generally address the problem of industrial renewal after decline by identifying industrial regions and the industries within them, and analyzing their cultural, social, economic, and political characteristics in order to identify actual or potential sources of renewed competitive advantage.

This dissertation follows in this tradition but takes an alternative approach. Rather than using a geographic region as an analytical starting point, this project begins with a small and specialized industry. This industry is called Robotics Systems Integration (hereafter alternatively referred to as "systems integration," or "integration"), and its business is to design and install robotics automation systems for manufacturers. Although this industry plays an important role and has a presence anywhere manufacturing takes place, it is especially concentrated in the states bordering the Great Lakes, often referred to as the "rust belt" because of their legacy of manufacturing vehicles, machines, and the raw materials that go into them.

The use of the robotics systems integration industry—rather than any of the regions within which it has a presence—as a starting point of analysis of industrial renewal is motivated by open questions in a body of thought called Evolutionary Economic Geography (EEG). EEG is, much like it sounds, an evolutionary framework for thinking about how economic activity takes place in time and geographical space. EEG will be discussed thoroughly in a later chapter. For now, the important point is that EEG emphasizes the role of history in shaping the economic present and future of a region, because history can reveal where this information was embedded and how it was transferred. New businesses and industries do not simply appear out of nowhere, but rather evolve from the system that already exists. Thus, EEG lends itself to the study of industrial renewal.

A key prerequisite to evolution in biology and economics is *variety*. Biological populations go extinct without sufficient genetic diversity from which to select in times when adaptation is necessary. EEG suggests that regional economies undergo similar adaptive processes, and that without enough variety in an economy, businesses cannot recombine ideas, technologies, or organizational strategies in ways that can continually adapt to global economic changes.

While there is evidence that economic variety does help to drive competitive regional economic paths (Neffke, Henning, & Boschma, 2011), the actual mechanisms for how diverse elements within an economy become matched and recombined, especially at the micro level, is still not clear. In delineating a research agenda for EEG, Boschma (2017) suggests,

> "…little to no attention has yet been paid to the role of agency, and the different types of agents that may drive regional diversification…[T]he regional diversification literature should incorporate a micro-perspective to understand which types of firms…and which types of individuals…make a difference (p. 358)."

Robotics systems integrators are precisely these types of agents. They work with a diverse set of technologies and industrial applications, as well as a diverse set of firms along the supply chain, so it is reasonable to suppose that they may help drive regional diversification and "make a difference."

This dissertation is aimed at understanding how robotics systems integrators traffic in this regional industrial variety, and what potential they, and by extension similar industries, may have for adjusting the paths of industrial regions.

1.2 Dissertation Outline

The dissertation proceeds as follows: Chapter two provides a review of the relevant literature on EEG and the concept of related economic variety, industrial decline and renewal, and the role of knowledge intensive business services (KIBS), a category of business to which integrators belong. Chapter three describes the conceptual framework for the research including the major research questions, as well as the study's design and methods. Chapters four through seven report and interpret the results of the research by topic. These include: the geography of integrators and their customers (chapter 4), integrators' innovation strategies and practices and position in the supply chain (chapter 5), integrators' role in facilitating related variety in a regional manufacturing ecosystem (chapter 6), and integrators' human capital practices (chapter 7). Finally, chapter eight summarizes the research, answers the research questions, and discusses contributions and implications for policy and further research into industrial renewal.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1 Robotics Systems Integrators and Integration

Robotics systems integrators are typically small companies. Leigh and Kraft (2017a) find that the median size of an integrator establishment is 20 employees, although responses to the survey in this project suggest it is closer to 50. Two large firms—Rockwell Automation and Lincoln Electric—with regional offices throughout the U.S. account for just over a quarter of total integrator employment (Leigh & Kraft, 2017a). Most robotics integrators provide general industrial automation systems integration, so in addition to robotics projects, they may also work on projects in which robots are not used.

While robotics integrators are located throughout the country, they are concentrated most heavily in rust belt locations, with the Milwaukee, Cleveland, Detroit, and Chicago MSAs among the highest-ranked in terms of integrator employment (Leigh & Kraft, 2017a). The geographic distribution of survey responses confirms this pattern.

Robotics systems integration is a sub-category of the broader activity of systems integration, which deals with any complex technological system, from information and communications technology to energy distribution (Hobday, Davies, & Prencipe, 2005). The concept of the integrator as a specialized individual or unit in the implementation of technical systems gained currency in the military during the Cold War years as weapon systems substantially increased in complexity (Prencipe, Davies, & Hobday, 2003). As military and other complex technologies transferred into the civilian world, the niche for the private systems integrator was created. Soon after, the widespread shifting of organizational strategies toward vertical disintegration, downsizing, and privatization reinforced the need for specialized systems integrators as large companies and government agencies that built and operated complex systems were not in positions to maintain these capabilities in-house (Tell, 2003).

Some large manufacturers have moved into systems integration as a strategy to increase revenue by capitalizing on the "value migration" from manufacturing to services (Davies, 2004), meaning that the provision of specialized services related to manufactured products has become more valuable than the product itself. This shift toward service provision has been identified as the "servitization" of manufacturing (Baines, Lightfoot, Benedettini, & Kay, 2009).

A classic example of manufacturing servitization is IBM's shift from a computer maker to an information technology solutions provider. In this case, the shift was complete: IBM is now solely a service provider.

One of the primary services that industrial automation product manufacturers began to offer was systems integration. That is, in addition to simply selling industrial automation equipment, they also consulted with customers about how to use the equipment most efficiently and to incorporate it into existing production systems.

For example, the large industrial controls company, Rockwell (formerly Allen Bradley) employed this strategy. As Rockwell's core product, controls, became more complex and their customers (manufacturers) vertically disintegrated, shedding production engineering and support staff, Rockwell began offering on-site support and maintenance services for its controls customers (Baines et al., 2009). Currently, their extensive network of satellite integrator offices provides support and training services for their products, as well as comprehensive industrial systems integration services.

For industrial systems integration, Rockwell remains an exception insofar as it maintains an expansive service-providing network within its corporate tree (although it also has many partners—including integrators that participated in this study—outside of it). Most robotics systems integration firms are small, privately held companies with one or a few offices (see "General Results" section in section 3.3.3a). Although interviews with owners and senior staff members of integrators indicate that these firms were often founded and staffed by people who had professional experience in large automation companies or manufacturers, their role in servitizing manufacturing is one that was initiated independently—by one or several people who saw a business opportunity—rather than as an outgrowth of top-down corporate strategy.

It is also important to note that while integrators provide services to manufacturers, the products that they are "servitizing" are not their customers' products but rather those of industrial automation and robotics manufacturers. Thus, they occupy a unique position in the value chain: integrators are upstream of most manufacturers that use robots, but downstream of robot and industrial equipment makers.

This position is of particular importance when thinking about global knowledge flows and innovation, because the U.S. had ceded its expertise in machine tool manufacturing to Japan and Germany by the 1990s (Gertler, 2004; Mansfield, 1993). All major industrial robot makers are headquartered in Europe or Asia.[1] There are several

[1] One exception is the acquisition of Univeral Robots by Teradyne, a Massachussetts-based industrial controls and automation company in 2015. However, Universal Robots, now a division of Teradyne, maintains its headquarters where it was founded in Odense,

implications of these geographical circumstances. For example, rather than establishing networks of U.S. branches dedicated to integration services, European and Asian industrial robot makers instead partnered with existing American integrators to provide engineering and maintenance services for their machines. While the major foreign robot makers do have significant corporate and sales presences in the U.S., and offer technical and integration services to their largest customers (mostly in the auto manufacturing industry), most of the technical knowledge about their products appears to be embedded in a loose network of private integrators.

What do robot systems integrators actually do? A brief summary of a case study from the 2017 World Robotics Report issued by the International Federation of Robotics (IFR) provides a helpful illustration. The case study begins by describing a production problem: A German power transmission manufacturer needed its existing metal rolling mill to handle multiple types of jobs instead of just one. However, it was time consuming to retool and reprogram between jobs, and a new, more flexible mill was cost-prohibitive. So the manufacturer hired a systems integrator to solve the problem, which it did by using a six-axis robot to feed and extract the raw material at different points in the rolling process. The solution was less expensive than purchasing a new machine and greatly sped up production times (International Federation of Robotics, 2017).

The German-based integrator created a custom rail upon which to mount the Japanese-designed robot, fitted with a German-made gripper, to optimize a North

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Denmark. Also, Universal Robots makes only small, light "collaborative" robots. This contrasts with the traditional industrial robot makers, which, although they are making collaborative robots of their own, also offer extensive product lines and include heavy, large payload robots.

American machine tool (the rolling mill). This integrator combined codified knowledge and craft technology from three continents and various levels of technology classifications along the low-to-high-tech spectrum for this single robotics automation job.

This case study exemplifies two points of concern for this dissertation. The first is that industrial robots are not often useful as stand-alone machines, but rather as integrated components in existing production systems—a factor which must be taken into account when quantifying their impacts. The second important point is that the integrator in this study acted as a central hub for a wide range of knowledge and technologies. While it is unclear why this integrator was chosen for this job—that is, whether it won a bid or had an existing formal or informal relationship with the manufacturer—its custom solution involved knowledge that it had acquired from other jobs and that will likely become explicitly or implicitly transferred to other clients.

2.2: Evolutionary Economic Geography

If these clients tend to be in the same geographic region as the integrator (in the above case the manufacturer and integrator are roughly an hour's drive apart in Southwestern Germany), manufacturers of the region likely have a competitive advantage simply by being part of regional business networks and having better access to the integrator. Hence, the geography of robotics integrators is noteworthy because it indicates a potential industrial competitive advantage in the very places where traditional industries have experienced decades of decline. What are we to make of the fact that the geographical center of U.S. industrial robotics integration knowledge lies in the heart of the rustbelt? Evolutionary Economic Geography (EEG) may help theorize how this pattern emerged and what it could mean for the future of legacy industrial regions.

The fundamental concept of EEG is the idea that economic systems evolve in ways that are analogous to biological evolution. That is, they are 1) dynamic and never in equilibrium, 2) path-dependent, meaning that systems' present states at any time are affected by the entirety of their history—there are no "leaps," and 3) reliant on variety, selection, and replication for the system to reproduce itself (Martin & Sunley, 2015). While there are weaknesses in the analogy,[2] I focus on a rather narrow aspect of the EEG framework that is particularly applicable to robotics integration: *relatedness*.

Relatedness in EEG terms has rarely been explicitly defined (Tanner, 2014), perhaps because it is an intuitive concept. It may be most easily understood by examples: a medical device manufacturer would be related to an electronics manufacturer if the former uses the latter's patented optical technology. Likewise, these two firms may also use the same plastics supplier, indicating another kind of relatedness. In practice, relatedness is often defined implicitly by methods used to measure it.

Several types of relatedness have been identified, such as product relatedness, process relatedness, technological relatedness, skill relatedness, and input-output relatedness (Boschma, 2017). There are also several ways to measure the various categories of relatedness, according to Essletzbichler's (2015) summary:

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[2] It does not (or has not yet) been able meaningfully to distinguish between economic *development* and economic *evolution*, and it cannot account for the fact that human power both results from and shapes systemic conditions, which in turn alter developmental paths (Pendall, Foster, & Cowell, 2010).

1) By grouping detailed industries together based on detailed industry classifications (e.g. Frenken, Van Oort, & Verburg, 2007). This is similar to the way that industries are typically treated in agglomeration studies, except that more attention is paid to industrial mixes at fine-grained levels of taxonomy. For example, a regional specialization in both *forging and stamping plants* and *architectural metals manufacturers* (both subsectors of fabricated metal manufacturers) means something qualitatively and quantitatively different than dual specializations in *fabric mills* and *petroleum refineries* (two subsectors that are taxonomically farther apart). This method measures *product relatedness* and suffers from the same problem that complicates traditional agglomeration studies: that underlying relationships between firms and industries that make similar products are simply assumed but not empirically verified.
2) By measuring co-occurrences between industries in various activities, such as exports or patenting (e.g. Breschi & Lenzi, 2015). Patenting co-occurrence is an example of a *knowledge relatedness* measure. Again, the fact of co-occurrence does not necessarily mean that industries or firms are related through formal or informal ties.
3) By measuring resource use and flows, such as common human capital needs among industries, one industry's use of another's patents, or input-output tables. Similar human capital needs between two firms or industries indicates *skill relatedness*, while input-output relationships and patent use measure *input-output*, *process* or *technological relatedness*. These relatedness measures may be influenced by underlying errors in data (e.g. input-output accounts). They also

> commonly assume symmetry between related industries, while this may not be the case. To use Boschma's (2017) example, "computer hardware skills might be relevant for the software industry, but software skills may be of lesser value to the computer industry" (p. 355).

Despite technical drawbacks to each measurement approach, the advantage of using the concept of relatedness is that in contrast to pure concentration measures (e.g. the Hirschman-Herfindhal index) they may indicate *complementarity* in addition to similarity (Makri, Hitt, & Lane, 2010; Tanner, 2015). Related firms (or industries, depending on the scale) interact ecologically and may more directly explain evolution within a region.

These are essentially the mechanisms that Jacobs (2016) elucidated in her classic descriptions of urban innovative milieus and that would go on to become known as Jacobs externalities. In the case of the dressmaker who developed the brassiere, an entirely new product was created out of a solution to an existing problem (which, in evolutionary terms we may call a *mutation*), and its inventor was able to expand it into a business by virtue of existing customers as well as suppliers and labor from the local garment industry. In Evolutionary Economic Geography, the success of this product (and the new industry it spawned) would be called *regional branching*, and it was due to the *related variety* of diverse but complementary resources surrounding Mrs. Rosenthal, the seamstress-inventor.

Measurements of related variety can quantify (through any of the approaches described above) the potential for similar evolutionary developments to occur. For example, a region can be said to be more or less technologically *cohesive*, depending on how much related variety it contains. Based on research to date, cohesiveness appears to condition the entry and exit of industries in regional economies, such that entrants tend to be more related to a region's existing portfolio of industries than to industries outside the portfolio, while exiting industries tend to be less related to regional portfolio industries than they are to outside industries (see Figure 1). In other words, the entrance of industries into a regional portfolio increases regional industrial cohesion, while the exit of industries decreases it. There is evidence that the net effect of these exits and entrances maintains a relatively stable level of technological cohesion within regions over time in both Sweden (Neffke et al., 2011) and the U.S. (Essletzbichler, 2015).

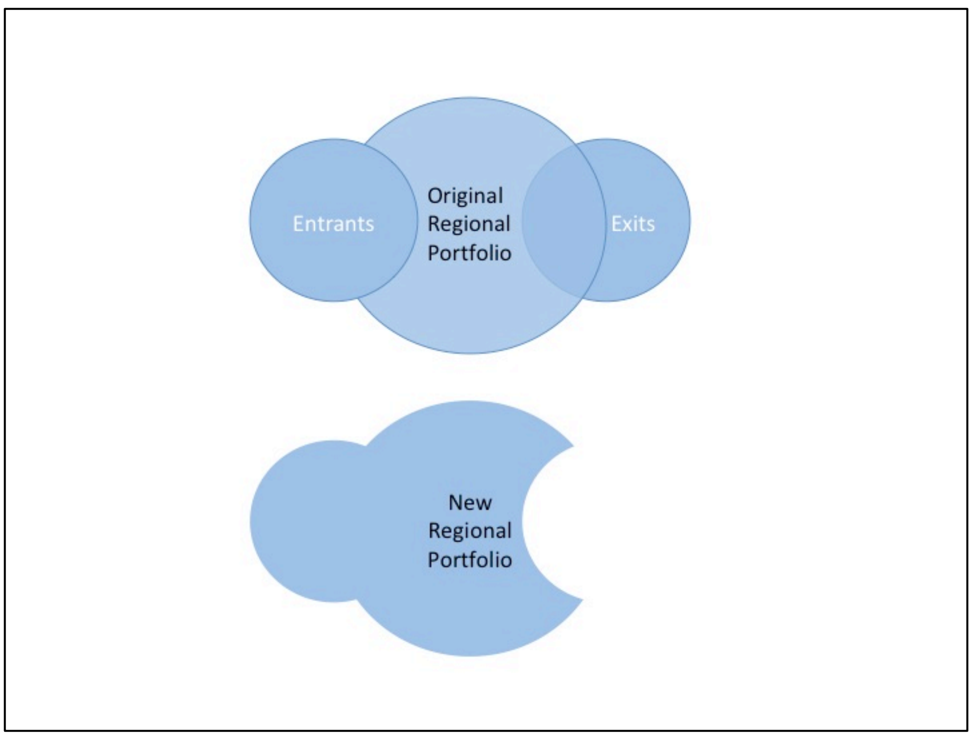


Figure 2.1: Regional Industrial Portfolio Evolution Due to Entry and Exit

While regional technological cohesion tends to remain stable, regional industrial portfolios do not necessarily have to. They may shift over time as the nature of entrants shifts. Essletzbichler (2015) suggests that there may be an optimal level of aggregate unrelated variety among firms entering a regional portfolio to ensure that the cohesion-increasing effect of exits does not lead to stagnation and lock-in. This type of regional adaptability and equilibrium-shifting is a key feature of resilience, which will be discussed in Section 2.3.

Further, both related and unrelated variety contribute to different types of innovation. Unrelated variety is associated with "breakthroughs," while related variety is more likely to produce incremental innovations (Castaldi, Frenken, & Los, 2015), again reinforcing the idea that some degree of both types of variety is necessary for regional evolution.

To date, evolutionary economic geography still lacks understanding of the actual mechanisms that drive industrial branching via related variety (Boschma, 2017). It is apparent that ideas from the fabricated metal industry make their way into the machinery manufacturing industry. But how do they get there? While there are unlimited paths along which this knowledge transfer can occur, they all involve people and networks. For example, employees could create spinoff firms based on technologies they developed while working at existing firms, or an engineering consultant may apply a solution developed for one client to a problem another client was having in a different industry. Either of these events could spur new firms of sub-industries, but socio-economic, patent, and input-output data cannot uncover these pathways, each of which have their own policy implications.

Studying robotics integration may expose some of these mechanisms, because the service that robotics integrators provide is essentially to relate knowledge and technologies. The relational role that they play is multi-dimensional: on one level, they relate various robotics technologies to each other (e.g. end-of-arm-tools to cables), and on another, they relate their clients (manufacturers of diverse products) to each other through the technologies they use. Finally, they relate the so-called "low-tech" legacy of many rust-belt manufacturing industries to the high-tech processes of 21st century industry. Relationships and innovation partnerships between high-tech and low-tech firms are not new, but have been overlooked in regional development (Hansen & Winther, 2011, 2014). Closely examining robotics integrators can illuminate these relationships by determining exactly where along the value chain new technologies, firms, or industries are being created.

2.3: Regional Resilience And Transitions In Legacy Industrial Regions

The evolutionary "way of thinking" (Martin & Sunley, 2015, p. 716) about economic geography lends itself to the study of regional economic resilience, because it characterizes development as the ability to adapt to changes and ultimately to survive. This stands in contrast to traditional neoclassical economics as well as economic development as it is commonly practiced, both of which characterize development as observable growth in generally straightforward indicators such as gross domestic product, employment, or wages.

An example of how these two perspectives (development as adaptation versus development as growth) can lead to different interpretations of regional "success" is the overgrazing of livestock. Overgrazing leads to a short-term increase in meat production, but eventual systemic collapse as grasses are consumed faster than they can regrow, leading to desertification of grazing land. A more easily recognizable industrial example is the “factory town,” or the overreliance of a community on a single manufacturing plant or industry cluster. The failure of the parent company or simply a decision to relocate production to a less expensive area can again lead to systemic collapse.

Neither of these situations would be described as resilient because they lead to comprehensive systemic collapse rather than the localized out-selection of undesirable systemic traits. Growth itself may be detrimental to an ecosystem if it compromises underlying robustness.

To be fair, traditional economics and economic development practice are not blind to resilience or adaptability. The influential work of the neoclassical economist Krugman (1991a, 1991b) introduced evolutionarily developmental concepts such as positive feedback mechanisms (e.g. firm and worker expectations and more generally, increasing returns to scale), path dependence, and emergence to explain continued uneven economic growth across space. However, evolutionary concepts of resilience have not been emphasized because of tradition, methods (formal modeling and empirical techniques typically assume linear relationships between variables and rely on proxy indicators for “black box” phenomena like social contact), and incentives (economic developers are evaluated on growth metrics (Dewar, 1998; Rubin, 1988)).

In the above examples, cultivating alternate food sources, implementing grassland management systems, or incubating spinoff technologies related to the dominant industry would constitute development in an evolutionary sense, but would be difficult to input into models, and could potentially depress growth in the short term since these measures would require some of the systems' limited resources.

Another reason for adopting an adaptiveness-and-resilience approach to economic development—as opposed to a purely growth-based approach—is that it is a normative and policy-relevant move that has gained currency in local and regional economic development and economic geography in recent years (Benner & Pastor, 2013; Leigh & Blakely, 2016; Martin & Sunley, 2015). In the wake of large-scale economic restructuring and advanced automation, researchers and policy makers are more inclined to assess the quality rather than or in addition to the quantity of change.

Thus, in both empirical and normative terms, Evolutionary Economic Geography lends itself to studying deindustrialization and resilience. After the Great Recession[3], there was a sense that the decades of decline in the U.S. industrial heartland had ossified into permanent economic disadvantage. However, thinking about the futures of these regions in terms of resilience rather than re-growth allows for alternative possibilities that do not simply replicate trodden paths (Christopherson, Martin, Sunley, & Tyler, 2014). Thus, one research question that this dissertation explores (see Chapter 3.1) is whether integrators, despite their small overall size as an industry, can play a significant role in

[3] The Great Recession is defined as lasting from December, 2007 to June, 2009, in keeping with the National Bureau of Economic Research's (NBER's) official definition (National Bureau of Economic Research, 2018). The fall and rise of real output of the US manufacturing sector closely follows this timeline (Federal Reserve Bank of St. Louis, 2018). However, US manufacturing employment was slower to recover than the general economy, continuing its decline until March, 2010, almost three quarters after the official end of the recession (United States Bureau of Labor Statistics, 2018). While employers may have "felt" the recovery in 2009 as orders and production increased, it is likely the experience of recovery did not saturate through manufacturing communities until hiring once again resumed. Thus, when annual statistics are used, 2010 will be considered the first year of the recovery.

the evolution and resilience in legacy industrial regions because of their relational capacity.

However, defining resilience for regional economies is contentious. "Engineering" (Cowell, 2014; Pendall et al., 2010) or "equilibrist" (Simmie & Martin, 2010) resilience is characterized by a return to a previous equilibrium after a shock. This is the kind of resilience sought in urban infrastructure. If a part of a water or power system fails, backup systems are (ideally) designed to restore proper function. This type of resilience framework is useful in some urban and regional contexts, especially in analysis of post-disaster recoveries (e.g. Berke & Campanella, 2006).

However, engineering resilience is not applicable for "slow-burn" (Pendall, 2010) challenges like climate change and deindustrialization. An alternative concept of resilience should allow for not only a return to multiple new equilibria, but also a variety of potential paths that can be taken to get there. Drawing on research from psychology and biological complex adaptive systems, Pendall et al (2010) suggest that *adaptive resilience* is a more apt concept for long-term problems. In contrast to engineering resilience, which is initialized at the moment of a system failure, adaptive resilience is a continuous process. Simmie and Martin (2010) call it an "ability," while Cowell (2014) calls it a "performance" (p.31), both implying that it is an actively expressed *quality* of a system rather than an *outcome*.

Regional economic resilience nevertheless remains a "fuzzy concept" (Markusen, 2003), because it is loosely conceptualized and, as the following discussion demonstrates, difficult to operationalize and measure. As such, it is better applied metaphorically than precisely (Pendall et al., 2010). However, the investigation of deindustrialization and its responses through a lens of adaptive resilience—albeit inexact—has led to a productive body of empirical work. One example of this is the development of a suite of quantitative measures that approach regional economic evolution and resilience holistically rather than as a simple measure of population or employment growth or decline.

For instance, Benner and Pastor create dual indices for both regional growth (including, for example, employment and earnings per job) and regional equity (including, for example, 80-20 household income ratio and African American dissimilarity index), and track metropolitan areas' progress (or lack thereof) relative to other metros within their census divisions over the period from 1980 to 2000. To explore possible correlates with the equitable growth indices, they regressed them against 26 more variables in the four broad categories of employment and industrial composition, geographic and distributional tendencies (e.g. whether the region has a state capital, and various measures of racial and ethnic segregation), workforce and housing, and regional interest in growth and equity.

While their research question is about equitable growth rather than resilience *per se*, it does cast rust belt regions in sharp relief from each other and from other regions in either category if we consider equitable growth a loose proxy for resilience. For example, while regions like Cleveland, Youngstown, Rochester, and Syracuse experienced relatively no improvements in either equity or growth, Cincinnati and Grand Rapids experienced marked improvements in both categories. Other places like Pittsburgh, Akron, and Buffalo saw slight improvements in equity, but not economic growth. The divergence of these findings suggests that traditionally industrial regions do not follow any kind of common or pre-ordained development trajectory.

But what leads to these divergent paths? Benner and Pastor suggest that the timing of the various aspects of development may play a role. In particular, greater regional equity may be a precursor to growth. Perhaps Pittsburgh's highly successful start—in terms of growth—to the 21st century was enabled by the ramp-up in regional equity leading into it (i.e. during the period from 1980-2000). Indeed, after further qualitative research Benner and Pastor suggest that in Cleveland, entrenched fragmentation driven by racial and economic inequity, has contributed to its inability to find a new equilibrium or path. That is, Cleveland never achieved an equitable foundation upon which to build. While negative "lock-in" is usually referred to in industrial or technological terms, this interpretation reminds us that lock-in can be political also, as is evident in the case of Cleveland.

Chapple and Lester (2010) take a similar approach, although one more explicitly focused on resilience. Again, starting with the change in a key indicator of resilience (e.g. 50-10 income ratio and real earnings per worker) over the two final decades of the 20th century, they compute regions' relative starting and ending points along the indicators' distribution. Those that started below the nationwide average but ended above it are considered "transformative," while those that started the time period with an advantage but ended below the average are "faltering." Stagnant regions remained below average the entire time, while thriving regions remained above. Rust belt regions for the most part land in the "stagnant" and "faltering" categories.

However, as the previous discussion suggests, resilience is not only about outcomes (equilibria) but also about paths. Accordingly, Chapple and Lester test for two resilience "typologies." The first is for new equilibria and the second is for a new path.

The latter test looks not at starting and ending points, but rather regions' relative changes in the relevant criteria in each of the two decades. Thus, if a region had a below average increase in real wages through the 1980s but an above average increase over the 1990s, it would be seen as transformative in the 'new path' typology.

Like Benner and Pastor, Chapple and Lester go on to identify factors that may contribute to resilience. They do this by conducting discriminant analysis on more than 40 demographic, economic, and distributional variables against the main indicators of resilience for each typology.

Both of these approaches to quantify resilience (or something like it) are intensive in terms of both computation and data. The outcomes of the analyses, in both cases presented as chloropleth maps accompanied by grids that indicate where on a resilience continuum each region lies, do not lend themselves to easy or intuitive interpretation. As high-level aggregate analyses tend to do, these methods obscure underlying counter-trends that are either too fine-grained for the data to pick up, or are not contained in the data in the first place.

Leaving these omissions aside for the moment, the results of these two studies are generally in agreement with each other and with Cowell's (2015) similar investigation. Regions that began the 1980s with a high concentration of manufacturing employment were not necessarily destined to stagnate or falter, but those that failed to recognize and adapt to economic restructuring and deindustrialization did not fare well. The latter group includes most of the core rust belt regions (e.g. Detroit, Cleveland, Buffalo, Rochester, and Milwaukee), but not some of the 'quasi'-rust belt regions like Columbus, Indianapolis, and Cincinnati.[4] Both Benner and Pastor and Cowell suggest that Columbus's resilience lies in historical and geographic circumstances and active adaptation. Columbus always had a light reliance on manufacturing relative to nearby regions, in part because a major land grant university and the state capitol provided sufficient and steady employment. Unlike Cleveland, Columbus was not geographically constrained by adjacent municipalities: easy annexation and a lack of interregional municipal competition made regional planning less fractious. Also, early in the era of restructuring, leaders in Columbus made a calculated push away from industrial development. In fact, Cowell suggests that one of the main differences in different levels of adaptive resilience of regions during the period of deindustrialization was the decision to double down on industry or to "bow out" of the competition altogether.

Of course, none of this evidence bodes well for the adaptive capacities of legacy industrial regions with "locked-in," undiversified manufacturing industries. It strongly suggests that a path change for struggling industrial economies is in order and that prescient regional leaders anticipated this necessity in successful regions. It also seems to confirm the "product-cycle" theory (Vernon, 1966), which predicts that as production activities become more standardized, they will disperse away from their original

[4] The terms "core" and "quasi" rust belt regions are used here to classify traditionally industrial metro areas according to Cowell's methodology, where core regions either intentionally or by way of the status quo maintained a heavy reliance on a relatively undifferentiated manufacturing sector as their economic bases through the 1990s, while quasi-rust belt regions made distinct, identifiable policy moves away from relying on manufacturing and toward service- or knowledge-based regional economic development. These are not intended to be definitive categorizations, since significant manufacturing activity remains in both kinds of regions.

geographic core regions to less expensive regions, leaving corporate and innovative functions behind.

However, it is also premature to marginalize or exclude manufacturing from this new path. While manufacturing in the U.S. has declined and dispersed overall (Norton & Rees, 1979), the nature of this change is far from complete or uniform across subsectors and places. In fact, manufacturing has remained remarkably "sticky" (Markusen, 1996) in the Rust Belt: the manufacturing (occupations) location quotient for the Midwest consistently increased from 1.16 to 1.38 between 1980 and 2010 (Doussard & Schrock, 2015a). All of the supposedly non-resilient regions examined above have gained significant manufacturing employment during the slow recovery from Great Recession.[5] Although some of these gains are related to auto company bailouts and a typical post-recession business cycle, the nation has not seen such sustained growth in manufacturing since the 1960s.

Many manufacturing subsectors, both mature and emergent, have remained in approximately the same "top five" regions (by employment concentration) from 1980 to 2010 (Doussard & Schrock, 2015b). For example, pharmaceuticals, commercial and service machinery, electronic equipment and components, and soaps and cleaning products all maintained four out of their original top five locations over the 30-year period. These industries followed the typical product cycle, meaning that they gained back-office design jobs at their legacy locations while production jobs were lost to less expensive locations. However, another group of industries managed to retain the same

[5] Based on author's analysis of U.S. Bureau of Labor Statistics Quarterly Census of Employment and Wages (QCEW) data.

degree of employment concentration in their core regions while preserving or growing the number of production workers relative to the number of design regions. That is, these industry subsectors (food, electrical/medical instruments, and aerospace) intensified productive capacity relative to design capacity (Doussard & Schrock, 2015b).

Looking specifically at the computer and electronics industry, Doussard and Schrock find evidence that despite significant overall employment declines in three original (1980) core regions (Minneapolis-St. Paul, New York, and Los Angeles), a stable base of production workers has remained. These regions all ranked in the top ten in computer and electronics production employment in the U.S. in 2010, but increased their share of production workers relative to design workers. In Minneapolis and Los Angeles, there were ten production workers for every seven to eight designers in 2010—a result that stands in stark contrast to the product cycle theory's prediction that production work should have cleared out of these places by now.

These patterns suggest that in evolutionary terms, regional industrial memory matters. Conceptualizing regional economies as evolving "portfolios" of more and less related industries helps to expose traces of historical paths that remain in current ones. The persistence of production work in Minneapolis' and Los Angeles' computer and electronic manufacturing sectors can be thought of as enduring *capacity*. According to Baily and Bosworth (2014), a nationwide lack of manufacturing capacity during the consumption glut of the 1990s and early 2000s was largely responsible for driving production overseas—not the search for cheap production as is typically suggested. The preservation of some manufacturing jobs throughout a larger-scale decline may itself be an element of adaptive resilience, warehousing crucial information for a time when conditions are more favorable for its activation.

This memory or enduring capacity can be highlighted qualitatively. For example, managers in the North Staffordshire (U.K.) region's ceramics industry note that firms remaining after the industry's "long decline" (finalized by the Great Recession) engaged in upgrading of both products and processes, sought technological synergies with nearby related (often high-tech) industries, and reinvigorated previously established collaborative relationships between firms and institutions. These measures were both purposeful and self-aware, reinforcing the idea that memory of historical assets is itself part of regional adaptive capacity (Tomlinson & Branston, 2014).

Likewise, a cluster of auto engineering and supplier firms remained in the English Midlands after the major anchor auto manufacturers closed their plants. These firms remained competitive due in part to continuing collaborations with nearby universities and corporate research centers, an existing reputation for quality work, and a facility with new technologies (Amison & Bailey, 2014).

These examples demonstrate the "Phoenix Industry" (Christopherson, 2009) model, where maintaining the human and physical capital that constituted the "initial advantage" of the declining region facilitates a rebound in a more favorable economic cycle. A phoenix industry does not simply "rise from the ashes" as an entirely new entity; rather, it maintains capacity in place enabling it to regain its previous advantage. Notably, in the North Staffordshire and Midlands cases, when exogenous conditions (e.g. falling value of pound, rising costs in China, growing cultural cache of place-bound manufacturing legacies) once again favored a return of production to these regions, the capacity remained.

In assessing Pittsburgh's transition from an economy-wide perspective, it does not appear to have much in common with these two British examples. With corporate and political interests eventually prevailing over citizen and labor groups (Deitrick, 1999), Pittsburgh shifted its economic development efforts away from steel production and towards medicine and robotics, among other high-tech sectors. Because Pittsburgh already had these assets in place at its major research universities (Carnegie Mellon and the University of Pittsburgh), this transition was historically contingent. However, this was a selective contingence, because it depended on that part of its history that did not involve the production of steel, which had been Pittsburgh's economic base until widespread mill closures in the 1970s and 1980s (Cowell, 2014).

Nevertheless, the steel industry played a role in Pittsburgh's transition even if it was not explicitly part of planning efforts: after the mills closed, steel-related knowledge and expertise remained in the form of "intermediate steel-industry suppliers" (Treado, 2010; Treado & Giarratani, 2008). Despite a lack of awareness of the existence of this cluster by local leaders, these generally small firms were able to maintain and expand ties to clients outside the region based on their international reputation within the materials industry. This cluster of steel specialists was also key in maintaining corporate and university research centers in the region, employing several thousand highly skilled scientists and engineers (Treado, 2010).

Robotics systems integrators—the firms with which this dissertation is concerned—are similar to these intermediate steel-industry suppliers. In fact, many of the firms that Treado refers to as “suppliers” would likely be called “integrators” in an auto manufacturing environment, because they both provide specialized production know-how. The above examples show that high-end expertise in mature industries does not necessarily disappear along with dominant regional producers. In some cases, these small specialists may increase their innovative capacity when they are no longer subject to the procedures and requirements of powerful clients (Christopherson & Clark, 2007). Doussard and Schrock (2015b) suggest that this tendency is more than anecdotal by showing that while original industrial core regions do not always maintain the same level of dominance, they do retain remnants of initial advantage that keep them competitive in global supply chains.

2.4. Knowledge-Intensive Business Services As Agents In Regional Economic Evolution

Like traditional neoclassical economics, Evolutionary Economic Geography still has a “black box” problem. Although the notions of relatedness, development paths, and adaptive capacity provide a more vivid and precise framework for theorizing growth than the traditional catch-all concepts of localization and urbanization economies, the actual pathways for how economically useful information moves and evolves or stagnates and disappears remain opaque. Despite many illuminating case studies, the sheer diversity of industries and places studied makes generalization difficult. At this juncture, the biological-economic evolutionary analogy breaks down: in biology, it is quite clear how genetic information—and adaptive or maladaptive traits—transfer from one generation to the next (for example, through sexual or asexual reproduction). In regional economies, the pathways are not so readily observable.

Neither biological nor economic evolution implies that outcomes are predetermined. Both are subject to random events or the emergence of unpredictable phenomena. However, in capitalist economies, human agency plays a significant role in determining which paths are followed and which are not. Pike et al (2009) and Bristow and Healy (2014) lay the theoretical groundwork for a more specific and human-centered evolutionary economic geography by emphasizing the role of agents in complex economic systems. Specific people or collections of people (e.g. firms, governing bodies, labor unions) must actively share (or withhold) ideas, knowledge, or processes for evolution to take place. Related variety is only "related" insofar as humans recognize the underlying relationships.

Studying robotics integrators can illuminate these relationships and their role in regional economic evolution because integrators, like steel suppliers (Treado, 2010), can be seen as *relational agents*. Robotics integrators transfer advanced production technology to manufacturers who may otherwise not have knowledge of or the capacity to implement it. They also may apply or modify production techniques across various industries, which is another mechanism for relation. Integrators may also swap employees with clients.

However, little is known about these types of agents or the roles they play in regional economic evolution. One of the main reasons for this is because, like steel suppliers, robotic integrators do "not fall into a single, or even a small number of industrial codes" (Treado, 2010, p. 106)**.** Integrators also occupy a different taxonomic branch than the industry they typically serve—manufacturing. Using the North American Industrial Classification System (NAICS) as an example, NAICS codes for manufacturers begin with a “3,” and additional digits are added to indicate further specificity about the products they make. At the three-digit level, it is possible to differentiate manufacturers of industrial machinery from manufacturers of transportation vehicles. However, the same level of taxonomic detail in the “Professional, Scientific, and Technical Services” category (under which systems integrators and steel suppliers would likely fall; see Table 1) does not differentiate between engineering service providers and public relations consultants, for example.

Table 2.1: Examples of NAICS codes used by Robotics Integrators Business Databases

NAICS Code	Description
54133	Engineering Services
54171	R&D in Physical, Engineering, and Life Sciences
541614	Process, Physical Distribution, and Logistics Consulting Services

Source: Mergent Intellect

To understand how robotics integrators may play an evolutionary role in a regional economy, it is necessary to understand the role of the category under which they are generally classified: knowledge-intensive business services (KIBS).[6] As large manufacturing firms “modularized” production (Sturgeon, 2002), they shed functions that either were not part of their core missions or in perpetual demand. These modular firms also acquired the organizational capacity to coordinate production-related tasks and modules across space and time. Thus, the importance of KIBS acting as outsourced service providers grew.

[6] KIBS are sometimes referred to as “Producer Services.” The former term is used in this proposal, but they are understood as equivalent.

There is already substantial theory and evidence suggesting that the presence of KIBS is beneficial for regional economies (Brenner, Capasso, Duschl, Frenken, & Treibich, 2018; Gallego & Maroto, 2015; Muller & Zenker, 2001). However, these findings have been presented tentatively because KIBS vary so much in the types of services they provide (Pina & Tether, 2016). Miozzo and Grimshaw (2005) show that clients of KIBS may not benefit unless they make organizational adjustments to absorb new knowledge and capabilities being offered to them from the outside. While KIBS may infuse new knowledge from outside of a region that otherwise would not be available to their clients, they also may act as "gatekeepers" and cultivate a position of power based on these knowledge asymmetries (Breschi & Lenzi, 2015). Sassen's (2001) seminal account of rising inequality within and among cities provides an example of the perils of such specialized knowledge consolidation.

Business service-providing KIBS (b-KIBS) and technical service-providing KIBS (t-KIBS) can be expected to impact regional economies in different ways. Indeed, Brenner et al (2018) find that t-KIBS (non-financial KIBS in their classification) benefit regional manufacturing sectors in Germany while b-KIBS (financial KIBS) benefit the rest of the regional economy. However, further discernment of differential impacts—between non-financial KIBS providing automation engineering services and product design services, for example—is restricted by industrial taxonomy limitations and data availability, discussed above. Quantifying the economic contributions of KIBS of all varieties is especially difficult because they are often intangible (Miozzo & Grimshaw, 2005). In the case of robotics integrators, they may have built and installed an actual robotic workcell, but in the process they also may have shown employees of the client special techniques for programming or troubleshooting robots. This information may have been communicated through formal, contractual training or through an informal demonstration. The problem of assessing systems integration is further compounded because an integrator's *product* innovation is the manufacturer's *process* innovation. The Oslo Manual (Organization for Economic Cooperation and Development & Eurostat, 2005) is clear on how to define innovations but does not provide guidance about whether the process or product perspective matters.

2.5. Knowledge Bases, Technological Intensity, and Industrial Heritage

One path to better understand differential local and regional impacts of t-KIBS like systems integrators and b-KIBS that provide financial, accounting, or marketing through the conceptual lens of differentiated *knowledge bases*. There are three generally recognized knowledge bases that constitute economic activity. They are *analytical, synthetic, and symbolic,* each describing a domain of human activities, competencies, and perspectives that foster productivity and innovative economic activity (Asheim, Boschma, & Cooke, 2011; Asheim & Gertler, 2006).

Analytical knowledge encompasses abstract, scientific knowledge, often resulting in radical innovations. Pursuits for which codified knowledge is an important outcome and an input (e.g. in the form of patents and publications) draw heavily on this knowledge base. Biotechnology and nanotechnology research are examples of fields that emphasize analytical knowledge. Researchers in these fields usually have doctoral degrees, because significant amounts of foundational knowledge must be accrued in order to make advances. Breakthroughs, like new drugs or nanomaterials, come from discovering new universal laws, often in basic research settings like universities, or from learning how to harness these laws in new products or processes, the latter often accomplished in corporate research and development labs.

Work that draws on a *synthetic* knowledge base usually involves applying existing knowledge to individual, often tangible problems, and relying more heavily on tacit and experiential knowledge. This type of knowledge is usually better transmitted in person, and often involves bringing together (synthesizing) various components, techniques, or ideas to solve specific rather than general problems (Asheim, Coenen, & Vang, 2007). Auto and machinery repair, manufacturing, and many kinds of engineering are synthetic activities. Disciplines and activities that are commonly referred to as artisanal or craft are synthetic knowledge-dominant.

Symbolic knowledge is employed in design work where aesthetics and brand identity are important—for example in industrial design or marketing (Asheim et al., 2011; Asheim & Coenen, 2005).

None of these knowledge groups are mutually exclusive, and many types of KIBS are difficult to assign to one or the other. For example, financial KIBS likely draw on both personal experience (synthetic knowledge) and understanding of business law and math (analytical knowledge) in designing financial instruments, while engineering KIBS need to understand the documented specifications of equipment with which they work (analytical knowledge) before they can fit it into a production system (synthetic knowledge). However, it is possible to determine which knowledge base is more dominant in an industry without extensive research. Robotics systems integrators appear to be a classic synthetic knowledge-dominant industry, as they develop mainly "one-off" solutions for manufacturing customers.

Asheim, Boschma, and Cooke (2011) assert, "The underlying idea behind the differentiated knowledge base approach is not to explain the level of competence…or the R&D intensity…of firms, but to characterize the nature of the specific (or critical) knowledge input on which the innovation activity is based" (p.898). Thus, the knowledge base approach has important implications for local and regional economic development, because it runs counter to the idea that certain industrial or occupational specializations based on "high-tech" or creative knowledge inputs are necessary for regions to maintain competitiveness, as has been the trend in regional development policy and practice in the late 20th and early 21st centuries (Tödtling & Trippl, 2005). Once it is recognized that innovation in fact does take place outside of traditional scientific research settings or design studios, policies that take into account the knowledge bases already in place can be tailored to regions (Asheim et al., 2011; Tödtling & Trippl, 2005).

For example, while proximity is important to innovation in all knowledge bases, the mechanisms through which it works are thought to be different. In work that draws on an analytical knowledge base, interactions are mainly "horizontal," meaning that scientists prefer to be around well-respected peers for brainstorming and idea spawning. Analytical workers also need physical access to the best-equipped laboratories, often furnished by universities or corporate R&D centers. Proximity in synthetic work is more often "vertical," meaning that problems are defined, addressed, and solved through user-producer interactions. In these situations, it may help literally to stand on the same shop floor to conduct a trial-and-error process together (Asheim et al., 2007). Both analytical and synthetic workers can be expected to value overall urban milieu less than symbolic workers who may find embededness in an interesting cityscape useful for artistic inspiration. Asheim and Hansen (2009) find limited evidence of this in Scandinavia.

While the knowledge base taxonomy presents an improvement over the traditional framework for thinking about the spatial aspects of innovation by being more inclusive of all types of potentially innovative activity and confronting the shortcomings of rigid occupational and industrial boundaries, several conceptual and empirical problems with the taxonomy remain. First, knowledge bases for the most part remain "ideal-types" of economic activity and have rarely been empirically described or verified (Manniche, 2012, p. 1284). Also, while they may strongly describe the innovation activities of individuals or firms, it is likely that complex combinations of knowledge bases will be necessary to foster innovation at the regional scale (Manniche, 2012). One contribution this dissertation makes is to look empirically at an industry subject to "*automatic* labeling" (Manniche, Moodysson, & Testa, 2017, p. 489, italics original) as synthetic (robotics systems integration) because it appears at first glance to fit synthetic innovation patterns, and confirm that these innovation patterns are actually aligned with the conceptual suppositions corresponding to the knowledge bases. Further, it assesses the spatial implications of the knowledge base classification of robotics systems integrators, paying special attention to issues of scale beyond the firm, such as how integrators recruit talent regionally or nationally, and how they seek and transfer knowledge.

These issues are of particular importance for integrators in legacy industrial regions because their synthetic-dominant industries are often classified as low-tech and considered irrelevant in contemporary economic development (Bender & Laestadius, 2005; Hansen & Winther, 2014). However, robotics systems integrators translate the products of analytical knowledge (e.g. developments in robotics and artificial intelligence) into practical solutions for manufacturers. Because of the structure of the robotics supply chain in the U.S. in which integrators play a central (and essential) role (see Chapter 6), it is fair to say that without them, the gap between end-users (manufacturers) and industrial robot suppliers would be large enough significantly to depress rates of innovation on both ends. So while integrators have a low measurable level of research intensity and thus are classified as “low-tech,” they are essential in the translation of highly researched innovations into practical solutions for end-users. This relational position gives low-tech regions an advantage upon which to build for growth and strengthen ties with faster growing “high-tech” regions.

2.6. Limitations to Generalizability of Inferences Based on Small t-KIBS Industries

While the research summarized in this chapter suggests that there is promise in more closely examining the potential of specialized industries that straddle the divide between legacy, low- and medium-tech businesses and the high-tech knowledge economy, this approach is not without limitations.

First, linking the success of a small industry like robotics systems integrators to the resilience of an entire industrial region is an empirically challenging task. Even in the regions where integrators have the largest presence, such as Milwaukee and Cleveland, they account for approximately one percent of total metropolitan employment.[7] It is unlikely that the necessary granularity of data for a long enough time period could be

[7] Author’s calculation based on unpublished data from Leigh and Kraft (2017) and BLS Quarterly Census of Employment and Wages, 2015 annual average employment.

collected to enable a confident determination that robotics systems integrators have a statistically detectable impact on one or more regional economies. The data needs and model would quickly become unwieldy, and the results may not be generalizable to other regions.

Second, even if a statistical link between integrator presence and regional industrial prosperity could be determined in one region, this relationship may be of limited practical value in the context of competing legacies and overriding conditions outside the region. This limitation may be especially evident in places like Detroit, where large, powerful corporations maintaining outsized influence over the local industrial ecosystem have interests that run counter to those of smaller firms and workers within the region (Harrison, 1997; Rutherford & Holmes, 2014). These interests could necessitate capital liquidation for short-term cash or shifting production and supply chains to areas with less expensive labor. Moreover, small and medium-sized businesses like integrators and their customers may lack sufficiently sophisticated business networks to seize upon and exploit a resurgence of local manufacturing (Amison & Bailey, 2014). Further research in this area could benefit from categorizing regions based on their industrial structures, in the tradition of Markusen et al (1996), where for example "Hub and Spoke" districts, which are dominated by large, powerful firms, may demonstrate resilience in different ways than "Italianate Marshallian Districts," which are collections of tightly networked smaller firms.

Because of these limitations, solutions to the problem of declining legacy industries and regions must address longstanding structural problems that have contributed to their decline. For example, Weiss and Bonvillian (2012, 2013) argue that substantial public investments on both the supply and demand sides in sustainable industrial technologies is a necessary precursor to overcome perverse incentives and entrenched routines in industries like energy production and agriculture. Others have suggested that interventions and investments be place-based to even out the self-reinforcing disparity between lagging industrial regions and highly technologically competitive regions (Atkinson, Muro, & Whiton, 2019). Clark (2014) suggests that strong local industrial intermediaries such as workforce development and business retention agencies would be needed. While this research does not explicitly examine these potential ingredients for industrial renewal, they are part of the industrial ecosystem and should be considered in future research and policy.

CHAPTER 3

RESEARCH QUESTIONS, CONCEPTUAL FRAMEWORK, AND RESEARCH DESIGN AND METHODS

3.1. Research Questions

Because little is known about the industry of robotics systems integration or its role in regional manufacturing economies, and because there is no way to identify integrators from public data sources such as those provided by the U.S. Census or the U.S. Bureau of Labor Statistics (Leigh & Kraft, 2017; Leigh, Kraft & Lee, 2018), some preliminary exploration into the process and business of robotics systems integration is needed. Thus, a major goal is to generate basic descriptive knowledge about the robotics integration industry's structure, geography, networks, workforce characteristics, and contractual arrangements, as well as recent (five year) changes and trends in these factors. This research goal calls for a statistically robust and representative sample (Remler & Van Ryzin, 2010), which is what the survey component of the project is designed to elicit.

However, given existing knowledge about integrators specifically and about the role of KIBS in evolutionary economic geography more generally, three targeted research questions can be formulated. Following Boschma's (2017) observation about the lack of insight into the agency involved in transmitting related variety (see Section 1.1), the primary research question is: *Are robotics integrators* ***relational*** **agents**? Here, the term "relational agent" is defined as an entity that introduces and cultivates related and unrelated variety in a regional manufacturing cluster. My proposition[8] is that robotics integrators are indeed relational agents.

A related sub-question is to determine the nature of the variety introduced and cultivated by integrators. In the literature, several dimensions of variety have been explored, including industrial (e.g. Frenken et al., 2007), technological (e.g. Breschi, Lissoni, & Malerba, 2003; Castaldi et al., 2015), between knowledge bases (e.g. Asheim et al., 2011; Pina & Tether, 2016), and along the supply chain (e.g. Essletzbichler, 2015). The initial proposition is that integrators are agents for increasing each of these types of related variety.

The second research question seeks to confirm that integrators do in fact rely on a synthetic knowledge base, in light of the observation that the industries that fall into the synthetic-dominant category have largely been assumed *a priori* (Manniche et al., 2017). Determining whether the synthetic knowledge base is empirically identifiable can add rigor to discussions of its incorporation into human capital research. A section of the survey addresses the human capital practices of integrators in detail and is designed to construct a profile of the knowledge, skills, attributes, and other characteristics that integrators seek in recruitment and that ultimately predict success of integrator employees. These questions also gauge to a limited extent the importance of synthetic versus analytical knowledge in robotics systems integration. Because the theory and literature on human capital motivating this research is partly outside the study's primary theoretical background of evolutionary economic geography, a full discussion of the

[8] The term "proposition" rather than "hypothesis" is used, because the testing will be performed using both qualitative and quantitative methods, and hypotheses are typically understood to be used in solely quantitative contexts (Remler & Van Ryzin, 2010).

relevant literature and research design for this portion of the dissertation is provided in Chapter 7.

The third research question is whether robotics integrators increase the capacity of local manufacturing clusters to be adaptively resilient. I propose that they play this role by being hubs for the storage and translation of related variety in manufacturing, reconstituting synthetic knowledge into competitive advantage-generating innovations, and thereby expanding the number of adaptive paths legacy industrial regions can follow.

In summary, this project asks the following three research questions:

1. **Are robotics integrators relational agents, and do they introduce related variety along the dimensions of**
    a. **Industry**
    b. **Technology**
    c. **Human capital (knowledge bases), and**
    d. **The supply chain?**
2. **Is a synthetic knowledge base dominant in the robotics systems integration industry?**
    a. **Do integrators rely significantly on technical labor?**
    b. **From where do integrators recruit entry-level candidates (e.g. local or national institutions; four-year universities or sub-four-year technical schools and community colleges)?**
    c. **Is on-the-job experience important for integrators?**
    d. **What individual human capital attributes most strongly predict success as a robotics systems integrator employee?**

e. **To what extent do synthetic versus analytical robotics-related skills predict success as a robotics systems integrator employee?**

3. **Do integrators increase the capacity of local manufacturing clusters to be adaptively resilient?**

These questions have been posed as straightforward "yes or no" questions because the intent is to test propositions developed from an evolutionary economic geography theory. However, in answering the questions, significant "how" and "why" questions will also need to be asked, meaning that this dissertation will contribute to describing in detail a complex and important but poorly understood process and advancing EEG empirics and theory. Finally, by knowing the locations of each of the integrators, it will be possible to determine whether the answers to these are questions are different, both qualitatively and statistically, for different regions—a finding that will be useful for creating targeted responses to technological change and manufacturing expansion strategies, especially in rust belt regions.

3.2. Conceptual Framework and Research Constructs

The introduction of variety is thought to happen mainly through supplier-customer interactions along the supply chain described in the previous section. Integrators infuse local manufacturing economies with novel robotics technology from outside the region that otherwise may not be accessible. They also may adapt techniques learned from clients outside of the region or in different subsectors or combine robotics capabilities with traditional industrial production techniques, as described in the illustrative example of the German integrator on page 8 of this proposal. This relationship is shown conceptually in Figure 3.1 where robotics technology from robot suppliers is introduced to integrators (orange arrows), who in turn apply it to specific problems of a manufacturer in their region (applied solutions; solid blue arrows). The knowledge gained from working on specific problems then becomes embedded within the integrator and the client manufacturer (applied knowledge; green dashed arrow). At this point, when applied knowledge is housed within multiple organizations in the same region, it is regionally embedded (orange embedded knowledge circle) and can be re-purposed and adjusted to solve problems or spur innovation in separate industries within the same region. This embedded knowledge flows circularly throughout the region as it is replicated, modified, and updated (signified by double-pointed arrows). This iterative, positive feedback-based process ultimately contributes to the adaptive capabilities of regional manufacturers as the store of embedded robotics knowledge builds through interactions with integrators.

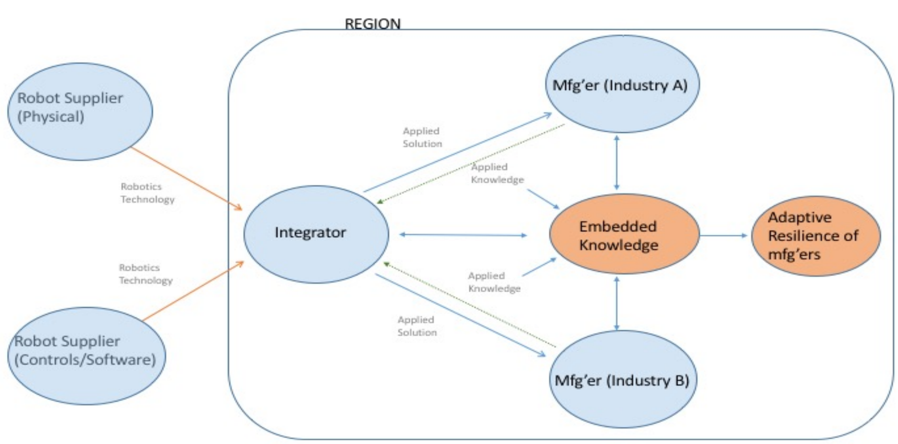


Figure 3.1: Conceptual Map for Integrators Acting as Relational Agents and Increasing Regional Adaptive Resilience

The occurrence of variety introduction can be detected directly in interviews by asking about how projects and solutions overlap for clients in different manufacturing subsectors. From the survey, variety introduction will be inferred from analysis of questions about the characteristics of integrators' clientele and the nature of integrators' projects.

As Figure 3.1 implies, the geography of integrators and their clientele is a key element to the theory being tested. That is, I expect a spatial aspect to the "travel" of technological variety, based generally on the agreement that space matters in technological development, and specifically, on Leigh and Kraft's (2017) finding that integrators are most heavily concentrated in the same places that robot-using manufacturers are concentrated (mostly the Midwest). Consequently, I theorize that integrators generally maintain a co-located client base.

Table 3.1 lists relevant concepts, constructs, and measures for answering these research questions. Except for the integrator database derived from Leigh and Kraft (2017) and background material cited in this proposal, all data come from semi-structured interviews and surveys of integrator establishments. Interview and survey questions are overlapping, but interviewees were probed for more detail on some answers, and were prompted to provide qualitative explanations rather than Likert-style ratings on questions asking about judgments and perceptions.

Table 3.1: Concepts, Constructs, and Measures

Concept	Construct	Measure
Geography of integrators and manufacturing clusters	• Customer base within region	• Driving distance to customers • Self-reported perception of integrator's importance to regional manufacturing; Self-reported perception of local manufacturing's importance to integrator
	• Attitudes about being located in region (e.g. no plans to leave or trying to relocate)	• Whether or not considering or planning relocation
Integrator human capital	• Education levels, backgrounds, wages of staff	• Composition of staff (e.g. engineers vs. technicians) • Relative importance of various knowledge, skills, and attributes of entry-level candidates • Difficulty in recruiting mid- and senior-level candidates
Integrators as relational agents	• Work with different types of robots	• Number and types of robot suppliers
	• Work with different types of robotics technology (e.g. machine vision)	• Number and types of robotics technology suppliers; which technologies
	• Work with different robotics applications	• Number of robotics applications with expertise; number used in typical project
	• Work with customers from different industries	• Number of manufacturing subsectors represented by customers
	• Supply chain determinants of learning and innovation	• Relative tendency to create standardized products or develop specific solutions to each new project • Relative importance of strategies for solving specific problems • Relative importance of strategies for staying up-to-date about robotics technology • Degree to which solutions for one customer translate to solutions for other customers

3.3. Research design and methodology

This research is a mixed-methods case study of U.S. robotics integrators, relying almost entirely on originally collected data from semi-structured interviews and surveys (recall that it is not possible to identify robotics integrators in publicly available data, so data collection is an essential component to this dissertation). The reason for using both interviews and surveys in this research design is that both "large *n*" and "small *n*" (Remler & Van Ryzin, 2010, p. 58) data are needed. Interviews will provide nuanced descriptions about the process and business of robotics integration, as well as enable tentative causal inferences about integrators' role in variety cultivation and adaptive resilience. At the same time, integrators are a small enough population (N = 518 according to most recent count) that a relatively small-scale representative survey can yield findings that are generalizable to all integrators.

This mixed strategy answers both "variance" and "process" questions. Variance questions are traditionally associated with quantitative studies, where the goal is to model the influence of changes in one or several distinct variables of interest on other important variables (Maxwell, 2012). The survey will be designed to answer variance questions such as determining the relationship between integrators' geographic locations and the industrial diversity of their customers (e.g., do integrators in the rust belt tend to have more fabricated metal manufacturers as clients than those located in other areas?). Interviews emphasized process questions such as determining the role of local industrial culture on the ability of integrators to provide adaptive solutions for clients.

According to Yin's (2013) case study typology, this study is considered "type 2" (p. 50) because it is a single case study of the robotics integration industry with multiple embedded units, which are the individual integrators. Although regional differences of integrators will be emphasized, the unit of analysis for this study remains the integrator itself. If this topic were to be studied further, it would be helpful to conduct a multiple case study comparing two or more regional clusters of integrators where the regional cluster would be the unit of analysis.

3.3.1. Research Component 1 - Semi-structured Interviews with Integrators

The initial strategy in recruiting interviewees was to recruit five interviewees each from both the Cleveland, OH and Boston, MA regions to enable a comparative case study. There were several reasons for this specific comparative geographic design. One is that Cleveland and Boston are both leading "robotic regions," ranking in the top ten in overall robotics related employment in the US (Leigh & Kraft, 2017a). However, the characters of their respective robotics industries appear on the surface to contrast with each other. Cleveland's Integrator-Supplier ratio (the ratio of integrator employment relative to supplier employment within the region) is 0.97, indicating that applied robotics is the dominant activity there, while Boston's is 0.14, which suggests instead that developing new robotics technology is the dominant activity. The presence of one of the world's leading robotics research groups at MIT and the headquarters of MIT spinoff Rethink Robotics reinforces the supposition that robotics R&D is the dominant activity in Boston.

Furthermore, the manufacturing clusters of the two regions are different. Cleveland, with 14.3% of its workforce employed in manufacturing, is much more dependent on manufacturing than Boston is, with only 7.6% working in the sector. While Boston has a notable competitive advantage—defined by a location quotient over 1.5—in only two manufacturing subsectors (computers and electronics and leather and allied products), Cleveland has significant advantages in eight diverse subsectors, including electrical equipment and appliance manufacturing, fabricated metal manufacturing, and chemical manufacturing.

Despite the initial plan and rational for interviews, it soon became clear that given the difficulty of recruiting integrators for interviews, the quotas from each region would not be met. Thus, recruitment was opened up to all regions, and a total of 11 integrators were interviewed, representing six states. Out of an abundance of caution in preserving the anonymity of study participants, respondents are aggregated into collections of nearby states called Census Divisions (see Figure 4.1). Interviewees represented four Divisions, as shown in Table 3.2.

Table 3.2: Interviewees by Census Division

Census Division	**Number of Interviews**
New England	4
East North Central	4
South Atlantic	2
West North Central	1
Total	11

Interviews were semi-structured as a compromise between the rigid control imposed by totally structured interviews and the fluidity allowed by unstructured interviews. The survey component of the case study introduces generalizability and structure, so the interviews do not need to be so tightly controlled. However, because the project asks specific research questions which only tangentially relate to individuals' experiences and emotions, a moderate degree of focus is also called for. Semi-structured type interviews are often used for questions about complex phenomena that involve interactions between organizations, people, and policy (Young et al., 2018).

Interviewees were owners or top-level executives at the integrator establishments, and most interviews lasted about an hour. Respondents were probed (Remler & Van Ryzin, 2010) to offer causal explanations for answers to some questions.

With the exception of one interview conducted in person and recorded on a handheld recording device, all interviews were conducted and recorded via BlueJeans web-based conferencing software. Interviewees were given the option to use the video and voice functions or just the voice function. Two interviewees chose the video and voice function, while the others (except for the one in-person interviewee) used voice only. All recorded transcripts were transcribed by the Rev.com transcription service, which uses a combination of artificial intelligence and human techniques.

3.3.2. Research Component 2 - Surveys of Integrators

Like all surveys, this survey has a unique set of challenges and advantages and requires a "tailored" design (Dillman, Smyth, & Christian, 2014). The questionnaire was designed and administered in Qualtrics XM web-based survey software and enabled for computers and mobile devices. It included 67 questions, although since many questions were only displayed conditionally on answers to other questions, no survey respondent was required to answer all 67 questions.

Since the “Census” conducted by Leigh and Kraft (2017) in 2015 identified only 518 integrators nationwide, the entire population could theoretically be emailed a questionnaire. However, obtaining valid email addresses for all 518 integrators was not possible. Thus, the population of integrators was divided into two groups based on the likely accuracy of email addresses. The first group (Group 1) was provided courtesy of the Robotics Industry Association (RIA), and consisted of 135 of their integrator members. This list is maintained and updated continuously by the RIA for its correspondences, so the accuracy of contacts is expected to be high.

The second group (Group 2) was generated from the remaining Leigh and Kraft (2017) database not included in Group 1. The website of each integrator in the database was searched individually for appropriate email addresses for survey distribution. Group 2 was then divided into two further groups based on the type of email address that was found. Group 2a includes 16 integrators that provided emails for specific contact people within their organizations, while Group 2b contains 105 generic email addresses that were not associated with a specific employee of the establishment. These email addresses often begin with “sales@” or “info@” so it is expected that the chances that they will be directed to an appropriate employee may be low.

Survey invitations and reminders were sent over the period of late March to early June, 2019. The first set, sent on March 27, 2019 went to 20 email addresses from Group 1 and functioned as a pre-test. After one week, several responses had been recorded without problems, so invitations to the remaining 105 members of Group 1 were sent. All invitations to Group 1 were sent directly from an RIA email address to improve the credibility of the survey. Invitations to Group 2 (non-RIA members) and reminder emails to Group 1 were sent from the researcher's institutional email address, with Georgia Tech's logo embedded in the email, again to improve credibility. Invitations to Group 2 were sent in Mid-April, several weeks after the initial emails to Group 1. The delay in initial distribution to the two groups was due to the extra time it took to manually generate the mailing list for Group 2 using the process described above. Finally, on June 3, 2019, a final reminder email was sent to Group 1, directly from the email address of the executive director of the RIA.

While it is not ideal to have initial contact between the groups separated by several weeks, it was determined that, due to the time constraints of the project, the group with the highest expected response rates (Group 1) should be contacted as soon as possible, and that Group 2 would be generated while waiting for Group 1 responses. There were no major shocks to the manufacturing or systems integration industries during the approximately two-month period of survey distribution, so the time of response is not expected to influence results.

Forty-five surveys were at least partially completed, although the number of observations for individual questions tends to be slightly lower, because not all respondents answered every question. One response was removed from analysis because it was from an establishment based outside of North America.

Table 3.3: Survey statistics

Links sent	Links **not** returned as undeliverable	Surveys Started	Surveys Completed	Response Rate (Completed/ Delivered Links)	Yield Rate (Completed/Started)
268	251	87	45	17.9%	51.7%

The response rate, which is the number of completed surveys divided by the total number of survey links assumed to have been delivered via email (accounting for seventeen invitations that were returned as undeliverable) is 17.9% (Table 3.3). Similar surveys conducted within the last decade had higher rates, such as Helper and Kuan (2016) at 37% and Hatch (2013) at 46%. Response rates to the integrator survey would ideally be higher, but in light of the limited resources available for this survey (e.g. one researcher and no budget), and the phenomenon of declining social science survey response rates in recent decades (Tourangeau & Plewes, 2013), these responses should be viewed as acceptable and representative of the small industry.

However, because the Qualtrics survey software used for administration of the survey has the capability of tracking how many surveys were started—meaning how many recipients actually clicked on the link they were sent—it provides a better idea of whether the receipt of a survey was acknowledged. Not counting survey invitations that were explicitly returned as undeliverable, surveys may not have reached eligible participants due to redirection to spam boxes, unattended email addresses, or rapid deletions of incoming mail. Using those invitations in which the survey link was actually clicked on as the denominator (surveys started), an alternative and much higher *yield rate* of 51.7% can be calculated.

Survey results are reported in their unweighted form, because without a publicly mandated survey identifying the robotics systems integration industry, no sufficient benchmark against which to weight responses exists. This survey is in part an effort to confirm Leigh and Kraft's robotics census (2017), so using this prior work as a weighting mechanism would be inappropriate.

The responses align closely with Leigh and Kraft's robotics census along the key dimension of geography. At least half of the observations in each are from the East North Central or South Atlantic Census divisions (see Table 4.2 for this comparison; Chapter 4 provides a longer discussion of the geography of integration).

However, responding integrator establishments appear larger on average than the robotics census suggests, with a median size of 58 employees, compared to the census's median size of 20 (see Section 3.3.3a).

3.3.3. Summary Statistics from Integrator Survey

Summary descriptive statistics from the integrator survey are displayed in the following tables.

3.3.3a. Establishment Size

The survey estimates integrator establishment size in two ways. One question asks integrators to select the employment size range into which their establishment falls, producing Figure 3.2.

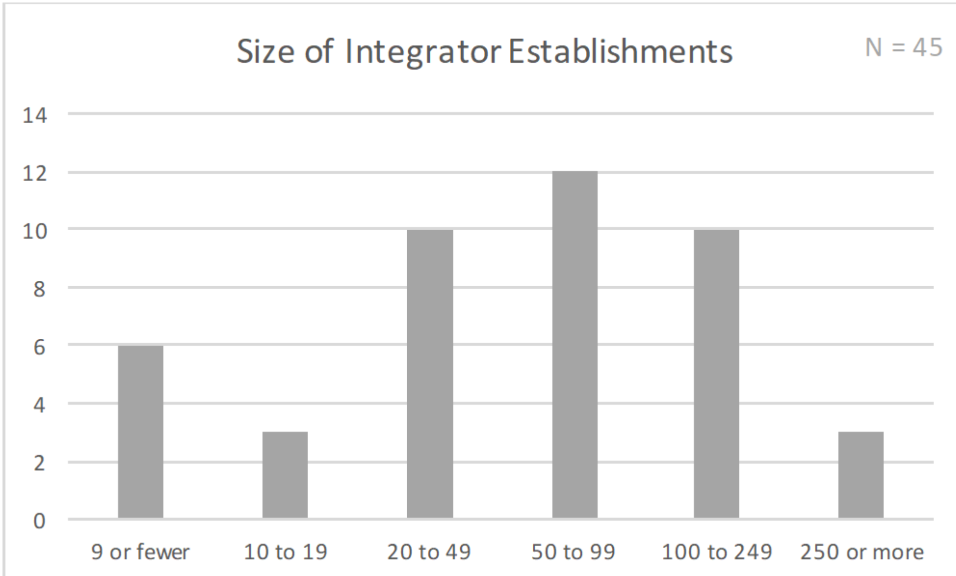


Figure 3.2: Integrator Establishment Size (number of employees)

Most survey participants' establishments have between 20 and 250 employees, with the largest single size range being 50 to 99. Employment size can also be estimated from a separate question asking integrators to enumerate the number of employees with various job functions by totaling the job groups across each establishment. From these responses, the median integrator size is 58, while the average size is 50. The largest total employment reported is 245, and the smallest is 4.

The actual median size of integrators is likely somewhere between the census median of 20 and the survey median of 58. The census median may be depressed because employment information was only available for two-thirds of establishments, with the rest being assigned the median value (Leigh and Kraft, 2017). Conversely, the median size for survey respondents is likely inflated, because the distribution strategy biased it toward RIA members: 38 respondents are members, while 7 are not. RIA members may be larger establishments with more capacity to participate in associations and related activities.

For analytical purposes, integrators can be generalized as small businesses, with only a handful of integrator establishments overall having more than 250 employees.

Most integrators (56%) are single establishment firms, although clearly a significant portion has multiple establishments also.

3.3.3b. Establishment Age

Most integrator establishments (64%) participating in the survey were founded prior to 2000, and the rate of integrator entrepreneurship is slowing. Whereas from 1990 to 1999, 13 of the participating integrators were established, only nine trace their origins to the first decade of the 21st century. Seven were founded in the 2010s (although data collection ended roughly 18 months before the end of the decade).

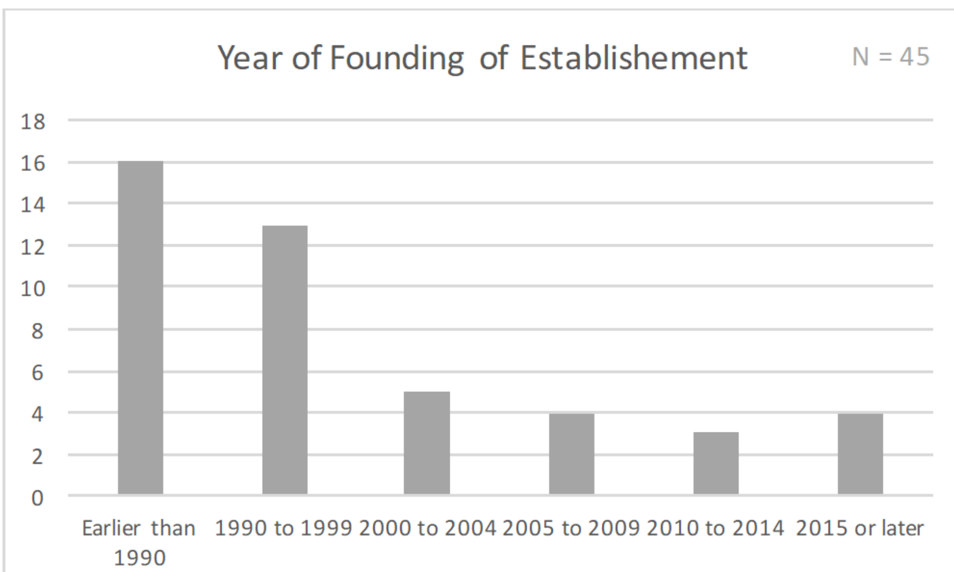


Figure 3.3: Year of Founding of Establishment

3.3.3c. Ownership and Acquisitions

As presumed, integrators are mostly “mom and pop” firms, meaning that they are privately owned, and not under any larger corporate umbrella. 34 integrators reported being owned by an individual, family, or small group of owners, while five are owned by a larger company (one of which is a private equity firm). Two integrators are employee owned.

Still, acquisitions are not uncommon in the integrator industry. This was apparent anecdotally from news of Lincoln Electric, a transnational welding supply company already with some robotics integration capabilities, acquiring several integrators in the last several years (Lincoln Electric Holdings Inc., 2015). The survey confirms that acquisitions are indeed occurring. Six establishments experienced a change in ownership since 2014, and four of these were due to an acquisition by another firm. Nine integrators responding to the survey also acquired other establishments in the same time period (two both acquired and were acquired by another establishment).

3.3.3d. Cost of Integration Services

Studies of the impacts of robots have relied on robot hardware prices alone to estimate the changing costs of robots. It has been recognized that integrations ads a significant cost (Hunt, 1988), but no current estimate of these costs has been conducted (Leigh & Kraft, 2017a). This survey asks how much a typical integration project costs and what percentage of this cost is for robotics hardware as opposed to integration services.

Most integrators' typical projects cost between \$100,000 and \$500,000, while a few tend to do much larger or smaller projects.

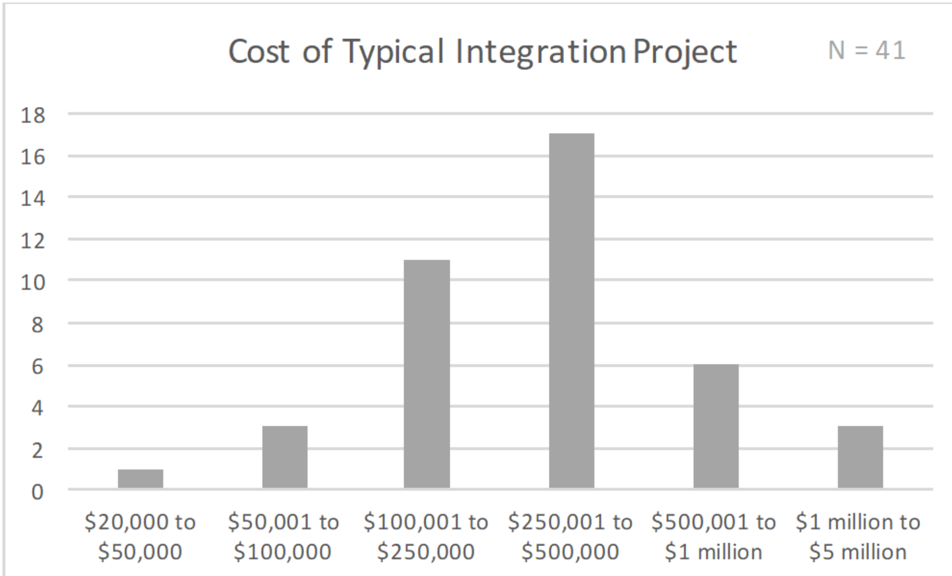


Figure 3.4: Cost of typical integration project

Importantly, integrators estimate that 31% of these costs are for the actual hardware, meaning that the remaining 69% are for integration services. This confirms that value in the robotics supply chain lies heavily with the integrator, and also suggests that even as the prices of robots continue to fall, small manufacturers will still face cost barriers to using robots because of the high expense of the technical knowledge required. On the extreme end of integration costs, three separate integrators reported having completed projects that cost $20 million.

3.3.3e. Difference in Responses Between East North Central Integrators and All Others

Because answers to the research questions relate to some extent to differences in regional integrator clusters, t-tests were performed for all applicable questions to test the difference in mean values of responses between integrators in the ENC division and in the rest of the county. While there are several notable differences—which are discussed throughout the dissertation where applicable—most results show no statistical differences based on census region. This lack of statistical differentiation is to be expected with this small sample size. For some questions, more observations could lead to more discernable differences between regions. In some cases, a statistical difference is detected, but is likely spurious because F-tests suggest that the distributions being tested have unequal variances. More observations also would have allowed for a more fine-grained grouping of regions for these tests. In order to achieve comparable test groups, they were grouped as those in the ENC division versus those in all others. Thus, it is not possible to identify nuances particular to, for example, the South Atlantic cluster of integrators. Selected t-tests and f-tests are displayed in the Appendix.

CHAPTER 4

GEOGRAPHY OF ROBOTICS SYSTEMS INTEGRATORS

4.1 Introduction

Answers to the research questions posed in this dissertation depend on the geographical relationships between integrators and current or potential customers and related businesses. Earlier research on the geography of the robotics industry suggests that integrators are significantly co-located with related manufacturers and customers (Leigh and Kraft, 2017), but whether this proximity can be translated into competitive advantage, especially for legacy regions, remains to be determined. This chapter lays the groundwork for moving beyond the appearance of proximity to uncovering its mechanisms.

4.2: Co-Location of Robotics Systems Integrators and Related Industries

Leigh and Kraft (2017) demonstrated that the U.S. robotics industry is statistically co-located with related manufacturing industries by comparing employment distributions of robotics and the other various industries among metropolitan and micropolitan areas. For example, the fabricated metal industry has a statistically significant 0.51 correlation coefficient with the robotics industry (see Table A3 in Leigh and Kraft 2017), meaning that metro areas with significant fabricated metal manufacturing employment are likely to have significant robotics employment also.

However, the measure used in Leigh and Kraft (2017) accounts for the entire robotics industry including suppliers, which have a different geography than integrators and are more concentrated in coastal metro areas. In Table 4.1, the top 20 metro areas in terms of integrator-only employment from Leigh and Kraft (2017) are listed along with location quotients of strongly related industries.

Table 4.1: Top Metro Areas in Integrator Employment and Location Quotients of Related Industries

Metro Area	Integrator Employment	Fabricated Metal (NAICS 332)	Machinery (NAICS 333)	Transportation Equipment (NAICS 336)	Engineering Services (NAICS 54133)
Milwaukee-Waukesha-West Allis, WI	8,874	2.65	3.17	0.67	0.67
Cleveland-Elyria, OH	8,198	2.68	2.00	1.18	0.68
Seattle-Tacoma-Bellevue, WA	5,302	0.62	0.54	S	1.20
Detroit-Warren-Dearborn, MI	1,762	1.84	2.20	4.69	S
Chicago-Naperville-Elgin, IL-IN-WI	1,333	S	1.05	0.37	S
Minneapolis-St. Paul-Bloomington, MN-WI	849	1.55	1.31	0.12	0.86
Kansas City, MO-KS	835	0.80	0.71	1.38	2.02
Iowa City, IA	750	0.36	0.35	S	0.45
Cincinnati, OH-KY-IN	704	1.39	S	1.79	0.94
Akron, OH	600	2.26	2.07	S	0.80
Wapakoneta, OH	600	S	S	S	S
Los Angeles-Long Beach-Anaheim, CA	564	1.12	0.52	0.92	1.03
Houston-The Woodlands-Sugar Land, TX	407	1.94	S	0.18	S
Grand Rapids-Wyoming, MI	389	2.57	3.10	S	S
Louisville/Jefferson County, KY-IN	383	1.30	1.16	2.58	0.54
Columbus, OH	358	0.77	0.85	1.25	0.83
San Francisco-Oakland-Hayward, CA	351	0.38	0.37	0.34	1.15
Toledo, OH	296	1.34	1.21	4.67	S
Boston-Cambridge-Newton, MA-NH	287	0.74	0.55	0.41	1.22
Charlotte-Concord-Gastonia, NC-SC	287	1.12	1.39	0.96	S

Integrator employment: unpublished data from Leigh and Kraft (2017)
Location Quotients: Bureau of Labor Statistics, Quarterly Census of Employment and Wages, 2016, Private establishments, annual averages.
S = Suppressed data
Location quotients over 1.1, indicating competitive advantage, are darkened.
Wapakoneta is a micropolitan statistical area, with more than 10,000 but fewer than 50,000 people, roughly 55 miles north of Dayton and 80 miles southwest of Toledo.

The three manufacturing industries, fabricated metal manufacturing (NAICS 332), Machinery manufacturing (NAICS 333), and transportation equipment manufacturing (NAICS 336), were included in the list because several sets of evidence suggest that they are both most strongly co-located with and related to robotics systems integrators. In Leigh and Kraft (2017), these three subsectors had the strongest correlation coefficients of colocation with robotics in metropolitan areas. The International Federation of Robotics data also shows that these three subsectors were among those with the largest operational stock of robots in North America in 2016[9] (2017). Finally, survey results in Chapter 6 (Figure 6.3) show that these three subsectors, along with "miscellaneous" manufacturing (NAICS 339) are the subsectors to which survey respondents' customers most commonly belong.

The chart shows that the metro areas that lead in integrator employment also tend to have strong specializations in the these manufacturing subsectors, indicated by the grayed-out cells. The association is especially strong for fabricated metal, where 12 of the 18 non-suppressed metros have fabricated metal manufacturing location quotients greater than 1.1 (1.1 is used here as the minimum threshold for comparative advantage). Several legacy industrial regions, including Milwaukee, Cleveland, Detroit, Akron, and Grand

[9] The IFR robot stock data use the Standard Industrial Classification (SIC) codes, which are not identical to NAICS codes but can generally be translated without much difficulty. According to the IFR, the equivalent of the rubber and plastic products (SIC 22, NAICS 326) and semiconductors, LCD, and LED manufacturing (SIC 261, NAICS 3344) industries had a greater operational stock of robots than fabricated metal (SIC 25, NAICS 332) and machinery manufacturers (SIC 28, NAICS 333) in North American in 2016. The question of why rubber and plastic manufacturers and semiconductor manufacturers have more robots than fabricated metal and machinery manufacturers but are less frequently reported as customers of integrators and less intensively co-located is an open one. It could be that these former order more robots per integration job, or that they tend to work directly with suppliers.

Rapids, on the list of top 20 integrator metros have very high location quotients—at least 2.0—in at least two of the three industries on the chart.

The engineering services subsector (NAICS 54133) is also included in the chart, because it is the classification to which robotics systems integrators should belong. However, it appears significantly less associated with integrator employment than the manufacturing subsectors listed before it. With the caveats that even at this five-digit NAICS level of specification, this category is very broad (including such disciplines as geological or civil engineering, which are not related to robotics systems integration), and many metro areas' data are suppressed at this level of detail, it suggests that integrator location is more closely tied to manufacturing industries, who are its customers, than to other engineers, who could be partners, competitors, or labor pooling co-beneficiaries.

The purpose of drawing out these associations between the geography of robotics systems integrators and their related heavy industries is to ground quantitatively the concept that the fates of integrators and the regions with these industrial legacies are intertwined. Throughout the dissertation, the idea of legacy industrial regions will be used as a generality and referred to broadly with terms such as the "rust belt" or its approximate multi-state Census Division equivalent, the East North Central division (see Figure) to preserve the anonymity of survey respondents. Like any "type" of region, the subset of industrial legacy regions is diverse and not amenable to any one-size-fits all resilience strategy. However, this section demonstrates that there is a type of American geographic region with significant integrator presence as well as significant manufacturing activity, and that is mostly but not exclusively found in the states bordering the Great Lakes.

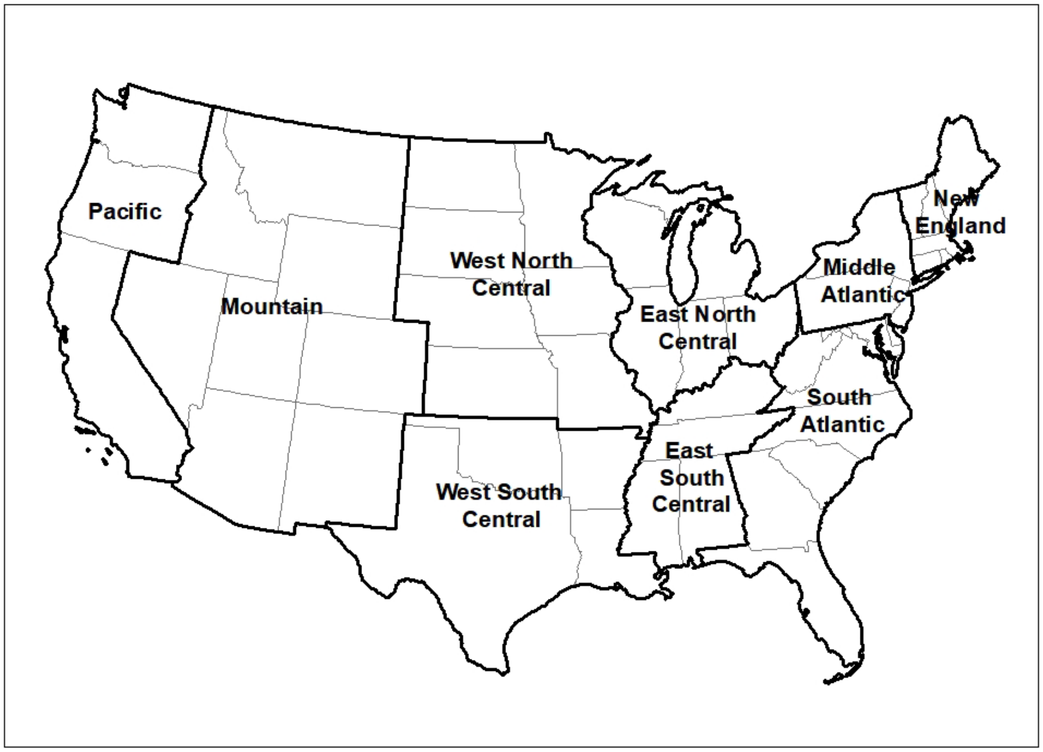


Figure 4.1: Census-Defined Divisions of the United States (source: Author's creation from US Census Bureau cartographic files; Alaska and Hawaii are not shown but part of Pacific division)

The geographic distribution of survey responses reinforces the existing picture of the industrial geography of robotics systems integration: Almost half of responses (22) come from the East North Central division, while the remaining 23 come from all other divisions (see Table 4.2). In Leigh and Kraft (2017), the ENC comprised 37% of responses. The other regions have similar representation under both data collection strategies.

Table 4.2: Geographic Distribution of Integrator Survey Responses by Census Division, compared to 2017 Robotics Census

	From Robotics Census (Leigh and Kraft, 2017)		From Integrator Survey	
Census Division	**Number of Establishments**	**Percent**	**Number of Responses**	**Percent**
East North Central	192	37%	22	48%
South Atlantic	68	13%	9	20%
Pacific	59	11%	3	7%
West North Central	46	9%	4	9%
Middle Atlantic	44	8%	2	4%
East South Central	33	6%	3	7%
West South Central	33	6%	1	2%
New England	22	4%	1	2%
Mountain	21	4%	1	2%
Total	518	100%	46	100%

4.3. Geography of Integrators' Customers

While it is reasonable to assume that integrators and manufacturers in close proximity to each other are more likely to interact than those that are distant, this assumption warrants empirical investigation. Perhaps integrators or other knowledge intensive business services (KIBS) conduct most business remotely and have significant client presences outside of their home regions. Pittsburgh, for example, retains a strong professional community of metallurgical scientists and engineers even after the region's capacity to manufacture steel had sharply declined (Treado, 2010; Treado & Giarratani, 2008). Instead of serving local clients, these engineers were forced to travel more often to their customers. In fact, the lack of sufficient direct flights from the Pittsburgh airport to accommodate consultants' frequent travel schedules was cited as a major challenge to the sustainability of this metallurgical science cluster (Treado, 2010).

Thus, a main question asked in the survey and interviews is: where are integrators' customers? The answer to this question yields a mixed assessment of the actual importance of integration to local manufacturers. Some integrators have a more locally-based clientele than others. Overall however, integrators travel frequently. As one integrator explained, travel is “part of the gig.”

In the survey, integrators were asked to estimate the percentage of their customers that fall within three categories of distance from their establishment: 1) within a 1.5 hour drive, 2) between a 1.5 and 4.5 hour drive, and 3) greater than a 4.5 hour drive. For ease of interpretation the first two categories can be collapsed into trips of 4.5 hours or under. Such a trip may be completed round trip with one overnight stay, and even at the distant end (4.5 hours) may not require air travel.

From 35 usable responses to this question, no overwhelming visible pattern is apparent (see Figure 4.2). While the 31-40 percent and 71-80 percent categories are common, there is no dominant integrator-customer locational relationship. Some integrators almost exclusively deal with customers over long distances, while some manage to maintain a more local customer base.

Most integrators, however, are somewhere in the middle, and have customer bases that are almost evenly split between local and non-local. While 16 respondents (46%) have at least half of their customers nearby (i.e. within a 4.5 hour drive), slightly more—19 (54%)—have half of their customer base beyond a 4.5 hour drive. The average respondent maintains about 56% of its customers within 4.5 hours.

Some integrators are on the extreme ends of the customer distance distribution: three respondents to the survey have over 70% of their customers within a 1.5 hour drive—constituting a very local customer base—while five maintain 70 percent or more of their customer base outside of the 4.5 hour threshold. Still, 13 integrators, or just over a third of respondents, report having 70% or more of their customers within 4.5 hours.

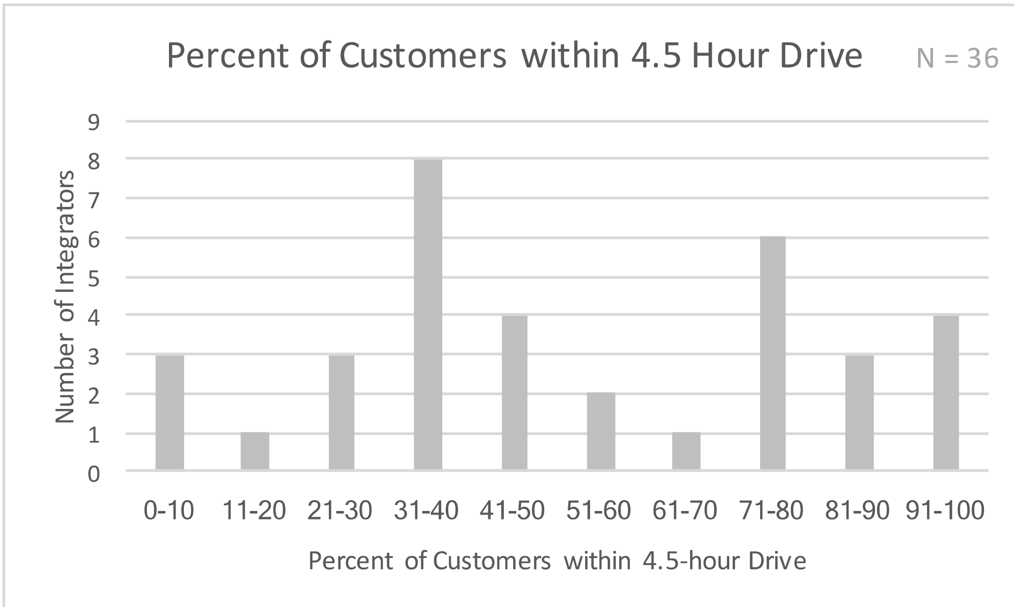


Figure 4.2: Number of Integrators by Percent of Customers within a 4.5-hour Drive

In line with territorial servitization theory, a working hypothesis for this investigation is that in regions with strong historical manufacturing presences, such as those located in the East North Central (ENC) census division, integrators would be more likely to have more customers in their home regions (as opposed to integrators located in regions without significant historical manufacturing concentrations). If KIBSs are indeed economically beneficial to their regions, one pathway would be by producing spillover effects through interactions and knowledge transfers to their local customers. This dynamic is assumed in quantitative KIBS investigations, but never directly tested.

The average percentage of customers within 4.5 hours is higher for respondents in the ENC census division than it is for those in all other divisions (61% versus 49%), suggesting that rust belt integrators do generally work with customers that are closer to them. However, a t-test reveals that the difference in means between the two groups of integrators—those in the ENC census division and all others—is not statistically significant (two-tailed p-value = 0.204; see Appendix A). Additionally, some integrators in Oregon, California, and Alabama report capturing a significant amount of business nearby. Perhaps with more observations, a statistically robust difference in means of customer distance based on location would emerge.

Manufacturers report a different story about the integrators they hire. In a different but related survey completed about two months prior to the launch of the integrator survey (Leigh & Kraft, 2019), manufacturers were asked whether they hired independent robotics systems integrators. Twenty-seven manufacturers reported that they hired independent integrators and provided both the location (state) of their production operations and their integrators' home base. Of these 26 manufacturing establishments, 18 hired integrators from their own states and another two hired integrators from adjacent states. Even those manufacturers that obtained more distant integrator services tended not to look very far: there were two Virginia-Pennsylvania pairings and one Indiana-Tennessee pairing, both of which could conceivably fall within the 4.5 hour drive threshold.

It is unclear what to make of the discrepancy between the geographical relationships between integrators and manufacturers as reported by both sides. One explanation could have to do with non-response bias in the manufacturing survey. Seventeen manufacturers reported using independent robotics integrators but did not provide a location for the integrator. These integrators may have been farther away from the manufacturers, making the exact location more difficult to recall, thus causing them to skip over the integrator location question. The location of an integrator is likely not of great importance to a plant manager, since the integrator is typically the one that does the travelling (although in one case an integrator did say that manufacturers commonly travel to the integrator). Conversely, integrators could be expected to have a better geographical perception of their customer base.

Either way, the geographical extent of this segment of the robotics supply chain remains unclear. Integrators travel frequently for work, but also tend to work for customers near their offices.

Interviews with integrators confirm this ambiguity. Integrators frequently report being in their current locations because of legacy. The founders—in several cases, a family member of current ownership or management personnel—often began the company because they were embedded professionally or personally in the community. For example, one Ohio business was founded by a former technician for a robotics company who was already living and working in the region. Although his two sons took over the business, they remained in the same area. In fact, they recently engaged in a partnership with a robot supplier with which they had not previously worked for the sole purpose of having the potential to work with two large manufacturers in the region who use the supplier's brand of robots. Another Ohio integrator had given little thought to opening another office even as more travel became necessary, because the expenses and inconveniences of setting up new infrastructure outweighed those of travel.

The travel involved in designing, engineering, and even constructing robotics systems is not considered extensive by integrators. All integrators interviewed build and test full systems in-house and then deconstruct them and ship them to customers.

Sometimes the installation of a system at a customer's facility is contracted to a local crew of technicians, but integrators often send a team to the site for a week or more for an installation and commissioning. An integrator in New England noted:

> "…outside of the installation piece of it, there's really no requirement for us to be there. Now, local support is always nice because manufacturers that want to lean on you or just put a project in, knowing that you're available to be at their beck and call is beneficial. But ideally, if we do it right, they don't need us anymore."

An integrator in the West North Central census division said that her firm's travel patterns are similar to those described above, although some complex projects require an advance team to work at a customer facility for up to eight months.

Some integrators suggested that the most travel-intensive parts ostf the business are sales and client relationships. An interview with two executives from an East North Central integrator produced the following dialogue:

> Interviewee 1: "I think visiting a customer [is] mostly client relations. If they have the drawings and specs, we can do most of it over conference calls, and engineers can draft something up, design in-house. So…engineers don't really need to go onsite to figure out how to integrate."
>
> Interviewee 2: "Yeah, being onsite ends up being more customer relationship building."

Another reason for integrators' geographic ambivalence is that they have an ever-present awareness of the importance of diversification. Since most interviewees have worked in systems integration, manufacturing, or both for several decades, they are conditioned to expect frequent and significant disruptions. This awareness is explicitly manifest in strategic efforts to acquire new technological competencies or to expand into serving new industries (discussed in Chapter 5). Less explicit but still noticeable is the awareness that the expenses of relocating to chase business does not appear to be a sustainable strategy. In other words, because manufacturing plant closings and openings, as well as business cycles, are so unpredictable, the most efficient strategy is to be near an airport with sufficient connections to new locations. Several integrators mentioned considering opening new offices: two specifically said they were urged to consider the Carolinas by supplier representatives who anticipated a shortage of integrator capacity in the coming years. However, none were especially eager to commit the resources to establish a new office.

Of 44 integrators who answered the question, “Has your establishment relocated or established a new branch/office in the last five years,” 21, or 47%, answered in the affirmative (see Table 4.3). However, 11 of these 21 relocated or established a new office in the same state as the original office, suggesting that these moves may be more about expanding firm space and capacity than geographic footprint. An additional six integrators reported that their establishments were currently considering establishing a new office or relocating to a different state (not included are three integrators that fall into both categories, meaning that they have already established a new facility in the last five years or relocated *and* are considering doing it again). In summary, out of 43 integrators that answered both questions, nine either have or are considering establishing a new location, and in three of these cases both apply. Five additional integrators have relocated or are considering it, but provided no information on the new or potential new location.

Table 4.3: Recent or Potential Expansions or Relocations

Location	**Have Expanded or Relocated**	**Considering Expanding or Relocating**
To different state	7	5 (3 of these have already relocated)
To same state	11	1
Did not indicate location	3	2
Reason		
To be closer to existing customers	2	3
To be closer to potential new customers	5	0
To be closer to skilled workers	3	0
To be closer to robotics and automation suppliers	1	0
To be closer to a major airport	1	0
To lower costs of doing business	3	1
None of the above	10	4

N = 44 (Have Expanded or Relocated)
N = 43 (Considering Expanding or Relocating)

There are no strongly dominant reasons for establishing a new office or considering it, although being closer to potential new customers appears to be driving the decision slightly more than other considerations. In retrospect, the survey would have benefited from differentiating between local expansions and more distant moves, because eight out of 11 same-state relocators or expanders chose “none of the above” when asked to provide reasons for establishing a new office or relocating. A reason not listed on the survey was simply the need for a larger or newer facility. In browsing the websites of several of the integrators who gave the “none of the above” answer it is apparent that some of them recently made local expansions, so it is possible that most of those who moved within the same state did so for this reason.

While anecdotal interview evidence suggests that integrators are or will soon be increasing their presence in the Southestern U.S., survey responses provide only very limited corroboration. Of the seven out-of-state movers, three did move from either the Middle Atlantic or East North Central census divisions to the South Atlantic, but two others actually moved in the opposite direction—from either the West South Central or South Atlantic census divisions to the East North Central divison. One moved from the West North Central census division to the East North Central, and another moved to a different state within the East North Central. From survey evidence, it appears that these moves, all of which were new branch offices and not relocations, are not necessarily favoring one region over another. In fact, in this very small sample, the "cradle" of integration—the East North Central division—received a net gain of one establishment.

Being located in the East North Central division also does not appear to affect integrator firms' ability to land lucrative projects. Recall from section 3.3.3d the three integrators that had completed $20 million projects. All three are in different states of the East North Central census division, and according to the survey East North Central integrators report higher values on average for their most expensive projects than integrators from other places ($4.5 million to $2.9 million, respectively). At first glance, East North Central integrators do appear to have an advantage. However, they also report slightly lower average project costs. More importantly, neither of these differences in costs is statistically significant ($p = 0.337$; see Appendix A), suggesting either that being in the East North Central division does not impact integrators' ability to generate revenue, or that the sample size is too small to make this determination.

In the case of the high cost projects, it is likely that their status as older (all three were established prior to 1999) and larger (all three have 100 to 249 employees) were more influential in their ability to win expensive projects.

Finally, integration is a global industry. While this research project generally tracks domestic geographies and networks, inferring global ties via supplier relationships and headquarters, there is evidence that integrators may be gaining a more international footprint also. Most integrators interviewed mentioned doing at least some international work. When given the opportunity to write open-ended comments in the survey, two integrators noted that they had recently opened up international offices. Both were working in Singapore, and one was additionally working in South Africa.

4.4. Industrial Legacy and Locations of Integrators

On one hand, integrators are actively relocating or expanding their geographic footprint: nine out of 43 (21%) have recently moved to another state or are considering such a move. If this trend continues, the geographical footprint of the industry will noticeably evolve in the next decade.

On the other hand, most integrators are not moving or planning on moving, and even some who have established new offices are doing so in the heart of traditional integrator territory. Why might this industry, in the words of Markusen, be so "sticky" (Markusen, 1996)?

The evolutionary economic geography answer to this question is "history," and responses to another survey question support it. In addition to asking whether integrators have or are considering moving, the survey also asked, simply, "Why is your establishment located where it currently is?" Eighty-two percent, or 36 out of 44 respondents gave the reason that it is near its founder or founders' place of residence, making it by far the most common of the eight choices given. Additionally, 17 out of 44 respondents (39%) listed proximity to founders' residence as the *only* factor in the establishment's current location, even though they were instructed to select all applicable choices. The next most common reason is that the current location is near existing customers, which is another indicator of history being important.

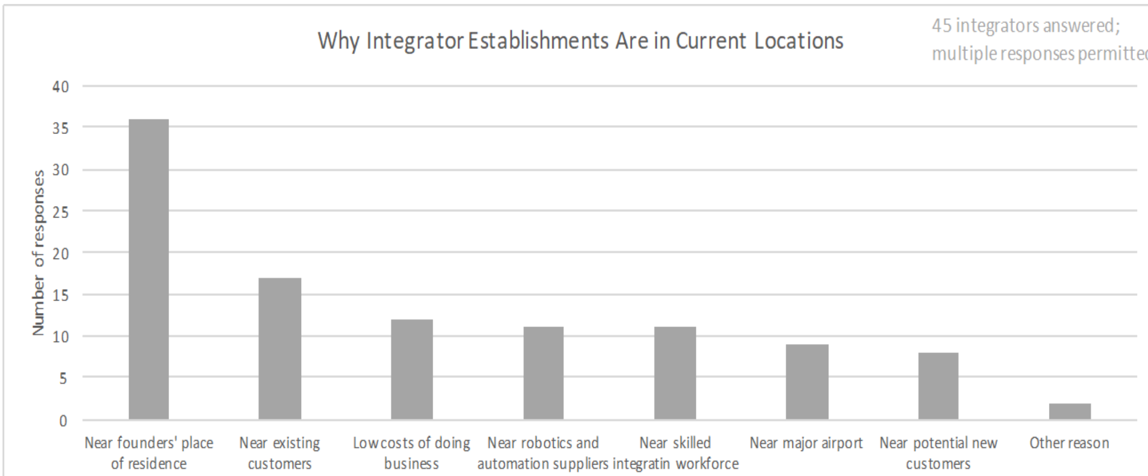


Figure 4.3: Reasons for integrators' current location

As interviews clarify, integrator firm foundings were often tied to existing relationships or circumstances in place. The following are paraphrases of five interviewees' origin stories

- The owner of a commercial and residential electrical contractor saw an opportunity to move into industrial controls when the industry moved to programmable logic controls from relay-based controls. He sought out a partnership with a controls company and became one of their integrators.
- A welding supply salesperson noticed that his customers had robots they were not using because they did not know how. He partnered with some investors to begin an integration business.

- A co-owner of a "hard" (non-robotic) automation company wanted to go more in the direction of robotics, so he left the business to start a new, robotics-focused automation firm.
- A tool-and-die worker started a systems integration business out of his garage.
- A rep for an early robotics company, anticipating its dissolution, purchased used equipment and hired some colleagues to start a robot refurbishment and distribution business, which eventually expanded into systems integration.

These stories are not very different from the classic garage entrepreneurship stories of Silicon Valley lure, but importantly, they all occurred in the East North Central, West North Central, or South Atlantic census divisions, far from the coastal areas that are known for their cultures of entrepreneurship and innovation. In each of these integration business origin cases, the founders remained in the same areas they already lived and worked, and began with local investors, customers, and employees. In the ensuing years, these businesses have not had reason to move. Further, two interviewees have assumed ownership of the business from their parents, and maintained its locations. These patterns strongly implicate history in shaping the current state of robotics systems integration.

4.5. Integrator Geography and Implications for Regional Industrial Renewal

In summary, both centripetal (inward) and centrifugal (outward) forces are at work to shape the geographical patterns of integrators. On one hand, community ties, longstanding customer relationships, and simple inertia are keeping integrators rooted in their legacy locations. On the other hand, the need to expand the customer base and the importance of face-to-face customer interactions means that integrators are frequently on the move and exploring expansions.

The implication of this dynamic for regional manufacturing systems is unclear. While integrators are concentrated in legacy industrial regions and have customer bases that ‘lean’ local, this arrangement is not the only viable model for the integration industry. Even when pressed about the importance of local ties, integrators tend to downplay them. When asked hypothetically what would happen if his business closed tomorrow, one integrator said,

> “The fact is, [in] the marketplace, there’s more supply than there is demand. If for some reason [my integrator company] disappeared off the face of the earth, I think that’s a void that would be filled.”

Subsequently, this respondent clarified that the statement applies most to his distribution agreements and that the engineering services may be more difficult to replicate, but the general point was that this integrator—though successful—lacked confidence regarding his firm’s value to the local industrial supply chain.

Survey responses show that integrators are more aware of their role in local industrial clusters than the above anecdote suggests. Responses to a question that asked integrators to rate their agreement with the statement, “My establishment helps to increase the competitiveness of the manufacturing community located within 100 miles,” on a scale from one to five (with “five” as strong agreement and “one” as strong disagreement) are high, averaging 4.41 (N = 44). This indicates that integrators generally do believe they are useful parts of local industrial ecosystems. However, when asked to rate their agreement with the same statement with respect to the entire country, the average score was slightly higher, at 4.66 (N = 44). So while integrators may be aware of their importance to their local communities, they may think more in terms of a national manufacturing supply chain.

Integrators are slightly less confident in the strength of their industrial knowledge milieu than they are in their importance to the industrial ecosystem. Two questions measure integrators' awareness of the amount of industrial robotics knowledge surrounding them. In these questions, they were asked to rate the strength of their agreement with the following statements: "Compared to other regions of the United States and Canada, there is a lot of industrial robotics knowledge within 100 miles of where my establishment is located," and "Compared to other countries, the United States or Canada has a lot of industrial robotics knowledge." For these questions, rated on the same scale as those described above, integrators were less confident. Average scores were 3.82 and 3.90 respectively, indicating that integrators recognize a knowledge advantage in their regions and in North America, but that they recognize it as a tenuous one.

There is one important regional difference in responses to this question. Integrators in the East North Central division, where they are also most heavily geographically concentrated, do perceive there to be significantly more industrial robotics knowledge in their region than in others in the U.S. The average response for integrators in the East North Central division is 4.43, indicating a moderate to strong recognition of local knowledge, while the average for those in all other divisions report on average a much weaker recognition of 3.26 ($p = 0.003$; see Appendix A).

For integrators, their ability to innovate does depend on their spatial relationship to knowledge and customers, but it appears to be secondary to the functions they actually perform. This is similar to what Doloreux and Shearmur (2011) find to exist in Quebec—that some types of services offered by KIBS firms are more dependent on proximity than others. While it is difficult to classify robotics systems integrators based on these authors' methodology, it appears that some of what integrators do falls under "basic process" innovations (i.e. innovations in production or organizational processes that are incremental and are likely to already have been undertaken by other similar firms) which *are* spatially contingent, while some falls under "major process" innovations (i.e. first-of-their-kind innovations in production or organizational processes), which *are not* spatially contingent (Doloreux & Shearmur, 2011). Again, integrators are not a perfect analogue to this example because an integrators' product is a manufacturers' process. However, the point of this example is to suggest that small innovations in how integrators operate may be more likely to come from informal regional learning, such as hearing that another nearby firm engaged in a specific upgrade, while radical innovations may be less dependent on proximity. An example of the latter would be an integrator solving a never-before-encountered problem for a manufacturer from a distant region.

Robotics systems integrators demonstrate "stickiness" in "slippery space" (Markusen, 1996). For the most part, their locations are remnants of regional industrial structures that are strongly entrenched but not totally stuck. Sunk costs of generational embededness are high. Legacy clients, continued facility upgrades, workforce relationships, and social ties are important. But none of these conditions guarantee prolonged regional synergy between manufacturers and KIBS.

That integrators are looking beyond their region for customers is not mutually exclusive to looking in the region, nor is it necessarily working against the generation of beneficial territorial servitization externalities. Working with a diverse array of manufacturers from various regions and industries could augment the capabilities they gain from trade shows, supplier trainings, and regionally-based manufacturers, as well as introduce new techniques that would not otherwise be accessible to the region. This infusion of learning from extra-regional projects could prevent “lock-in” and stagnation that can be problematic for old or insular industrial regions (Hassink, 2010).

Since integrator sales and marketing still rely largely on word of mouth and professional networks, an entry point for local or regional policy to facilitate these relationships could focus on information sharing and matchmaking. More research is needed to determine what policies could work.

CHAPTER 5

CUSTOMER-SUPPLIER RELATIONSHIPS AND INTERACTIVE INNOVATION

5.1. Introduction

Interpersonal and interfirm relationships at all points of the industrial robotics supply chain are strong drivers of the robotics systems integration industry's evolution. In this way, robotics systems integrators are similar to other "low and medium tech" industries, by prioritizing user-producer interactions to spur innovation and competitiveness (Hansen & Winther, 2014). The two most important types of relationships for integrators in the robotics supply chain are 1) upstream relationships with robotics suppliers, and 2) downstream relationships with customers. Maintaining strong relationships at both ends of the supply chain has several benefits for integrators, including assuring repeat-business from customers and favorable purchasing terms from suppliers. These types of relationship-derived benefits are discussed briefly in this section, but the main point of analysis is how integrators' relationships encourage innovation in applied industrial robotics and situate systems integrators as key agents in the process.

Integrator-customer relationships directly spur innovation because of strong "demand pull" in the integration industry, meaning that technological improvements generally come as responses to customer needs rather than through forward-looking strategic research programs (Di Stefano, Gambardella, & Verona, 2012). Integrator-supplier relationships play a secondary but still very important role in innovation providing integrators with up-to-date knowledge of emerging robotics products and capabilities and often assisting with specific projects.

I categorize both of these kinds of innovation as “interactive innovation,” because the knowledge involved and transferred is not easily codifiable, and often tacit (Gertler, 1995, 2003). While all innovation requires interaction between people to some extent, the distinguishing feature of the interactive innovation practiced by integrators is that the interactions cross firm boundaries. While biomedical innovations may be achieved by working interactively *within* a corporate or university research center, the driving force of applied robotics innovations is interactions *between* firms.

5.2. Interactive Innovation in Integrator-Customer Relationships

The survey operationalizes the degree to which interactive-innovation occurs in integrator-customer relationships by asking three sets of questions. The first pair of questions (Q1a and Q1b) asks integrators to describe the extent to which they try to standardize integration solutions or treat each new project as requiring a unique solution. The second question (Q2) in this series is, “How often does an integration project introduce a new method or technology to a customer?” This question is intended to measure the extent to which robotics process innovations developed by integrators are actually being transferred to customers (i.e. manufacturers).[10] Following from this

[10] This question could be problematic because of its lack of clarity about what exactly an innovation is, and because respondents may have a tendency to inflate their accomplishments. However, there are too many possibilities for what may actually constitute an innovation in systems integration to address each one specifically in a survey.

question, integrators are asked whether a solution for one project generates knowledge that the integrator can in turn offer to another customer (Q3). This question assesses the extent to which integrators not only learn from previous work, but also pass this knowledge on to other manufacturers.

The responses to each of these questions are scored on a one-to-five point Likert Scale, in which “1” would indicate the lowest level of agreement or occurrence, and “5” the highest. A low level of agreement with Q1a (indicated by a low score) is defined as indicative of interactive innovation, while high levels of agreement (high scores) indicate interactive innovation for the other three questions. Summary statistics, question wording, and scoring scales are shown in Table II scores.

Table 5.1: Interactive Innovation Scores for Integrators

Question	Q1a: Evaluate how accurately the following statement describes your establishment: My establishment tries to create standard or universal automation solutions, adjusting them only for specific customer needs.	Q1b: Evaluate how accurately the following statement describes your establishment: My establishment approaches each new integration job as a unique challenge, considering all possible concepts or approaches.	Q2: How often does an integration project introduce a new method or technology to a customer?	Q3: How often does a specific problem for a customer generate a new solution that you offer to other customers?
Mean	2.50	**3.84**	**3.13**	2.89
Mode	2	5	4	2
Standard Deviation	1.22	1.13	.89	.91
Scale	5=Extremely accurately 4=Very accurately 3=Moderately accurately 2=Slightly accurately 1=Not accurately at all	5=Extremely accurately 4=Very accurately 3=Moderately accurately 2=Slightly accurately 1=Not accurately at all	5=Always 4=Most of the time 3=About half the time 2=Sometimes 1=Never	5=Always 4=Most of the time 3=About half the time 2=Sometimes 1=Never

N = 44 for all questions

In general, responses to this set of questions indicate a fairly high level of interactive innovation by integrators. The average integrator rates the statement in Q1b as describing the firm's approach as characterized by each project needing new solutions at 3.84, which nearly falls into the "very accurately" category. Thirty out of 45 integrators responded either "4" or "5" to this question, indicating this type of continuous innovation based on customer needs is a defining characteristic of the business. While questions 1a and 1b are not mutually exclusive, and a high value for 1a—indicating that integrators try to develop standardized solutions to offer—does not necessarily imply a lack of innovative capacity, a higher value for question 1a does suggest that the responding establishment relies less on interactions with individual firms to innovate, instead developing and offering solutions to more universal problems. As the summary indicates, this approach is rare among integrators.

The responses to Q2 suggest that on average, an integrator's project results in a customer "learning" a new method or process more than half the time. Relatedly, the responses to Q3 suggest that the average integrator transfers a piece of knowledge or innovation developed for one customer to another almost half the time. Results from these two questions suggest that integrators routinely gain knowledge from working with manufacturers and are also able routinely to "transmit" and "re-engineer" (Muller & Zenker, 2001) this knowledge to others.

Interviews confirm and illuminate these survey results. Three themes related to customer-driven integration emerge. The first is that integrators' projects are highly unique and specific. The second is that the most successful projects result from the embedding of robotics systems knowledge within customer firm, something integrators refer to as being a "champion of the machine." Third, integrators do not think of this process as research and development (R&D), and instead simply consider these incremental innovations to be part of the job.

The uniqueness of projects results from the fact that even seemingly mundane tasks like picking up irregular objects or stacking trays on top of each other require intensive engineering. This is because certain fine-motor skills that are simple for humans remain difficult for robots. As such, small details can significantly alter the scope of a project and call for some of the most advanced robotics technology. In the "tray stacking" case recounted by one integrator, machine vision was needed. One integrator reported commonly assisting customers with *product* design so that the item being produced would be more amenable to robotic processes. For integrators, each new job requires some degree of innovation.

Because of the complexity of industrial robotics systems, they often require users to acquire new in-house capabilities to ensure the continued operation of the system. As one integrator put it: "…if they embrace the technology…the biggest thing we do from a training perspective [is] we try and find that person that's going to be the champion or the guy that's going to own the machine." While integrators try to minimize the work necessary on the customers' end, several noted that finding a person or team at the customer's facility to learn and embrace the new technology increases the productivity of the system as well as the likelihood that the customer will make future investments in automation.

Asking integrators whether they perform dedicated R&D was not part of the original interview protocol. However, in several instances, after interviewees described a robotics automation project to me, I remarked that what they were doing seemed like R&D. In these cases, they agreed that they were performing R&D even if they generally did not think of it as such. Some integrators report having spaces in their facilities dedicated to building prototypes or experimenting with new technologies, but again, these experiments are typically driven by customer demands. Self-funded, systematic applied robotics research is not common practice. One integrator remarked that his firm only began accounting for R&D as a dedicated expense when it was acquired by a private equity group. He notes that even after this new practice, the true costs of R&D are likely underestimated, because they are difficult to disentangle from regular project expenses.

Integrators' problem solving strategies also reflect this style of innovation. When asked to rank four problem solving strategies on a three-level Likert scale, with three being "very important," two being "somewhat important," and one being "not important," respondents rated "reviewing past documentation," and "trial-and-error" as significantly more important than hiring subcontractors or informally asking colleagues at other integrators firms (see Table 5.2).

Table 5.2: Importance of Problem Solving Strategies

	Informally ask colleagues at other integrator firms	Formally hire a subcontractor or consultant	Review documentation of past projects	Trial and error
Mean	1.54	1.36	**2.54**	**2.19**
Mode	1	1	3	2
Std. Dev.	0.75	0.57	0.50	0.66

N = 44 columns 1 – 3; N = 43 column 4

While integrators are proud of their self-sufficiency and ability to confront constant new problems—a trait that they highly value in potential job candidates (see Chapter 7)—this inward-looking tendency exposes the limitations of supplier-driven, interactive innovation: the results of incremental R&D are rarely disseminated. Trade secrets are valuable, and robotics systems are so unique that patenting them would simply publically disclose a partial solution to a similar problem that another integrator could exploit for free. As a result, much of what is learned builds up incrementally in-house, in internal documents and in the experience of employees working on projects.

5.3. Interactive Innovation in Integrator-Supplier Relationships

While much of the learning that integrators do comes from solving specific problems and accumulates more or less tacitly among firms and individuals, integrators recognize that industrial automation and robotics technology is progressing rapidly, and they value staying current on the latest capabilities. To assess the degree to which integrators proactively acquire knowledge, they were asked to rate the importance of seven different sources of information on robotics integration technology (sources are shown in Table 5.3) on the same three-point scale used in the previous table.

Two of the choices—"attending trade shows or industry conferences," and "obtaining training by supplier or training company"—are designed to assess the degree to which integrators interact with suppliers to help them learn and innovate. Note that some of the other choices involve interactive or tacit learning, but do not rely on interactions with suppliers. If supplier interactions are indeed important sources of knowledge and innovation, then these choices should score as high as or higher than the other sources.

Table 5.3: Importance of Robotics Knowledge Sources

Source of Information	Informal conversation with other integrators	Attending trade shows or industry conferences	Purchasing technology and "playing around with it"	Obtaining training by supplier or training company	Reading industry journals or magazines	Reading academic research	Recruiting employees with up-to-date knowledge
Mean	1.86	**2.45**	2.18	**2.64**	1.89	1.50	2.02
Mode	2	2	2	3	2	2	2
Std. Dev.	0.68	0.54	0.72	0.53	0.53	0.50	0.54

N = 44 columns 2 – 7; N = 43 column 1

Table 5.3 confirms that not only is in-person interaction the chief learning pathway in the robotics integration industry, but supplier-offered trainings and trade shows (where suppliers demonstrate their products) prove to be the most important ways for integrators to stay current. In contrast, sources of knowledge codification, such as academic or industry publications—while not completely unimportant—are certainly less useful to integrators than are sources that require their physical presence and interaction.

Interviews also confirm this pattern. Interviewees stressed that while both conferences and trainings are time and resource consuming—they almost always require travel—they are invaluable resources for staying competitive. One interviewee illustrated this by observing the following related to integrators' attendance at trade shows:

> "They've got a year's worth of problems that they've been presented. They've got all these 'I wish I had, I wish I could, I wish I knew,' in the back of their mind, and they go to something like [a trade show], and…just walking around, oh, that! Here, I need to talk to you about this…they build this little rolodex of 'now I know when that comes up…'"

While the predominant innovative force for robotics systems integrators is the imperative to solve customers' unique problems as they arise, suppliers assist and augment these solutions through continued partnerships with integrators. Elements of this relationship include regularly being available at trade shows (exemplified by the above quote), providing regular meetings and trainings, and in some cases providing direct assistance with a problem. For example, one integrator interviewed received assistance from a local supplier's office for a specific machine vision application that a customer required.

5.4. Unpacking the Integrator-Supplier Relationship

The nature of the integrator-supplier relationship is one of the most difficult aspects of robotics supply chain to understand. At the outset of this dissertation research, it was clear that suppliers rely heavily on integrators to get their robots into production systems, but it was also clear that most suppliers maintain a network of branch offices with engineering and integration capabilities in the U.S. This situation would appear to set the two up as competitors, with suppliers having the upper hand by having unfettered access to the robots themselves. Given this supposed power dynamic, it seemed even more counterintuitive that integrators commonly advertise on their websites some type of certification or partnership with multiple robot suppliers. If suppliers have leverage by being both competitors and maintaining control of the main product—robots—shouldn't they be able to demand exclusivity from integrators?

After conducting interviews, it became evident that the reason for this counterintuitive arrangement and the general lack of exclusive partnerships between suppliers and integrators is rooted in the history of the U.S. robotics industry. Specifically, because of the way industrial robots diffused in the U.S., integrators maintain significant leverage over suppliers by being the primary relationship holders with and main points of access to current and potential robot users.

The U.S. only briefly had a homegrown robotics industry, and by the early 1990s, it had been bought out and absorbed by European and Asian robot makers (Associated Press, 1990; Fanuc, 2019). Rather than develop an extensive sales and integration network, these foreign robot makers relied on the small existing network of American robot technicians and other industrial controls and "hard" automation (systems that cannot be easily retooled or reprogrammed) engineers. While nobody to date has written a history of the robotics industry, this strategy was presumably because it has only been fairly recently that robotics technology has become sufficiently advanced, accessible, and inexpensive to be used at a significant scale anywhere but in the largest production facilities—mostly automotive plants (Leigh Kraft Lee). Through the turn of the 21st century, it would have been rational for robot makers to focus their sales efforts only on the handful of plants that could afford and staff a large, roboticized production line.

As robot technology improved and became less expensive leading to growth in the potential population of robot-users throughout the 2000s and 2010s, integrators had already begun cultivating relationships with these manufacturers through other types of projects. Most integrators examined in this research were established prior to 2000 (see Figure 3.3). Only two out of the 11 firms interviewed specifically began as robotics systems integrators. The others were established as general automation and controls engineering firms and moved into robotics as opportunities arose. In some cases, robot suppliers recruited integrators as partners, while in others, integrators made strategic decisions to go into robotics and sought out partnerships with suppliers. Either way, robot suppliers appear to have traded a degree of control and exclusivity over their products for the convenience of a ready-made sales and engineering network.

Integrators explained in interviews that they continue regularly to forge new supplier partnerships with little if any pushback from existing supplier partners. In these partnerships, integrators receive sales leads, discounts on robots, and access to meetings and trainings where they are updated on the latest technology. While it appears that suppliers receive little in return—essentially a promise to use their robot, incentivized by a discount—the benefit they derive from this arrangement is significant: it gives them access to the entire U.S. manufacturing base with minimal internal investment in sales or integration capacity or personnel.

While integrators generally downplay the geographical element of integration as it relates to their customers (see Chapter 4), their comments indicate that territory is important to suppliers. As one integrator put it,

> "the regional sales offices are part of…their branding process. It's part of their marketing process. It's part of their technical support process, because they have local staff that they can send out. If you're in Southern California, for example, you might not want to fly all the way to Rochester Hills to sit down and ask to meet with [Robot Supplier X] personnel when they have an office in Southern California and you can just go there. It's all of that, really. They have all these regional sales guys. They all have sort of a home base. They have technicians that they can send out from the home bases."

As it stands today, integrators report that robotics suppliers still usually provide their own integration services for the largest projects (sometimes subcontracting with other independent integrators for specific areas of expertise) and are content to refer smaller jobs to their network of integrators. Most integrators noted that their partner suppliers remain important sources of sales leads, although they understand that the leads they receive are selective. One integrator recognized,

> "all the manufacturers have an integration division panel that's owned by what we refer to as the mothership, but sometimes it's a separate silo within the company and sometimes it's part of their robotics division itself. Some of them, almost all of them focus on automotive. And some of them focus on automotive and then like [Robot Supplier Y] does a little bit of everything, but they tend to try and go after either automotive or big projects that would basically bankrupt an independent integrator. Big aerospace projects, big nasty risky stuff."

The largest systems integrator interviewed acknowledged that although his firm continues to seek out larger projects—potentially causing conflicts with suppliers—it has so far been able to stake out its own territory, and relationships with suppliers remain mutually beneficial. He also noted that as the industry stands today, “mom and pop” integrators continue to thrive without growing and seeking out larger jobs.

Overall, a loosely tiered system with regard to the size of job sought out by integrators appears to have emerged where small integrators—the bulk of integrator establishments—take on smaller jobs and the several large integrators and suppliers take on the largest jobs. With robotics demand high and increasing at the time writing, this structure appears to be working for all sizes of integrators and suppliers. However, it remains to be seen what will happen if demand softens or technology changes. For example, if robots become sufficiently easy to program and install—no longer requiring the extensive skill of integrators—will suppliers attempt to bypass integrators and sell directly to manufacturers?

The integrator-supplier relationship that currently exists can best be described as “loosely coupled” (Brusoni, Prencipe, & Pavitt, 2001), because it allows both integrators and suppliers to structure and re-structure their partnerships on a project-by-project basis. Integrators often have formal relationships with suppliers, sometimes including the designation of “certified integrator” for the robot supplier in question, but even when such agreements are in place, they are rarely exclusive. While 41 out of 44 integrators did indicate on the survey that they have formal relationships with at least one robot supplier, 30 out of these 41 (73%) use additional robot suppliers in their projects. Thus, almost three quarters of integrators are, as one interviewee described it, “brand agnostic” even when formal relationships are in place.

This arrangement is common for “multicomponent, multitechnology products” in which components and technologies evolve at uneven rates (Brusoni et al., 2001), such as robotics automation systems. An integrator’s usual role is to do exactly as their name implies and integrate all of the various components and technologies needed for a project (see Sections 6.3 and 6.4 for a discussion of the various technologies and applications integrators regularly work with) into a coherent system—allowing suppliers of the separate technologies and components to focus on their own area of expertise. However as some integrators have developed their own sets of expertise, they may subcontract with a supplier to provide a more narrow set of services.

Integrators generally prefer this loose arrangement and prefer to keep contracts and partnerships as minimally formal as possible. As a result, the maintenance of trust between integrators and suppliers is an important aspect of business.

5.5. Conclusion

Robotics systems integrators are constantly innovating, although they tend not to think of their innovative process as research and development. Rather, it is driven by downstream interactions with customers (users of robotic systems) and facilitated by upstream interactions with robot suppliers.

Projects are typically one-off and spurred by specific technical problems from customers. Integrators' most successful jobs happen when a person or team at the customer's facility takes interest in and ownership of a custom-built system, indicating that knowledge transfer—and by extension, innovative capacity—from integrators to customers is an implicit goal of systems integration.

Suppliers assist in this process by providing leads and trainings to keep integrators up-to-date on the latest robotics technology. While suppliers have regional offices, integrators effectively function as sales representatives for robot suppliers to non-automotive customers in the U.S. This arrangement is loose and minimally formal, and integrators prefer it this way because it allows them to be nimble and open to more potential customers, which ultimately serve as the initiators of innovation.

However, this innovation system is not without drawbacks. For one, innovations developed by integrators are not only difficult to codify because of the lack of a platform or clearinghouse; integrators are in fact incentivized *not* to publicize their innovations to preserve their competitive advantage. While some integrators may publish YouTube videos showing systems at work (and be careful not to divulge how the system was developed), this is not an efficient or systematic way of publicizing innovations, so potential customers simply may not be aware of possibilities.

Another problem with interactive innovation is that since it requires interaction between a manufacturer and an integrator, it is highly subject to business cycles in the notoriously volatile manufacturing industry. Without customers, innovation stalls. Integrators hedge against this volatility in two main ways. One is by expanding to different regions and industries. Another is by cultivating and maintaining close, long-term relationships with customers. This strategy is reminiscent of the innovation-spawning relationships between auto-makers and suppliers described by Womack, Jones, and Roos (2007) in Japanese lean production systems. Looking at the machine tool industry, Anderson, Fine, and Parker (2000) suggest that machine tool makers partner with large customers to create a more continuous system of R&D. Integrators are partly engaged in both of these strategies. One integrator noted that their firm has actually re-designed parts for customers to make process design easier, while another claimed that their firm had essentially become the engineering department for a good customer. However, integrators occupy a different position in the supply chain than either machine tool makers or auto parts suppliers, so whether these strategies could become more codified in integration, or in regions where they are located, is unclear.

CHAPTER 6

RELATED VARIETY IN ROBOTICS TECHNOLOGY

6.1. Introduction

There is abundant anecdotal evidence that robotics systems integrators routinely work with a wide variety of technologies. An illustrative example of this technological breadth was given in the introductory chapter, where a case study of a project completed by a German integrator involving robotics and other industrial technologies from various locations and eras was summarized.

Whether this project was uniquely interesting and complex or a typical example of integrator work has significant implications for the conclusions of this dissertation. The ability to answer the first research question in the affirmative and confirm that robotics systems integrators are indeed relational agents depends on whether it can be established that integrators do routinely work with a variety of related technologies and industries.

This chapter reports the results of a section of the survey designed to answer this question for a representative population of U.S. robotics systems integrators. Based on the survey results, it is clear that integrators do routinely work with a substantial variety of robotics applications, technologies, and customers. At the end of the chapter, evidence from interviews is provided to support this conclusion with richer description.

The survey collects data on five main indicators of related variety. They are:

1) Industrial robotics suppliers used by integrators
2) Industrial robotics applications with which integrators have competence

3) Industrial robotics technologies with which integrators have competence
4) Manufacturing sectors served by integrators
5) Technological sophistication of customers

Data for these indicators of related variety are captured through a series of eleven questions on the survey, and further information was elicited through interviews.

6.2. Robotics Suppliers

One way to measure variety in robotics systems integration is by accounting for the number of different brands of robots used by integrators individually and in the aggregate. Some of these differences are nuanced and relatively minor, similar to the differences that only car enthusiasts notice in the quality of a ride. Others are more significant. Some of the most significant differences between robot suppliers relates to their corporate and geographical origins.

There are a number of firms that make industrial robots, and as of 2012, four of them were reported to have 17.1% of the Global market share (MarketLine, 2012). These are ABB, Fanuc, Kuka, and Yaskawa Motoman.

The survey asks integrators to identify which of the robot suppliers they use. To account for as many suppliers as possible, 14 robot makers and one "other" category were listed on the survey for respondents to choose from. Respondents were asked, "Which robotics supplier(s) does your establishment use for integration projects?" and instructed to choose all that apply.

Based on integrators' responses to this question, the U.S. market in 2018 appears significantly more concentrated than the global market did in 2012. Market share is approximated here by dividing the number of "uses" of each supplier by the total number of supplier indications of use (i.e. the "market"). The top four spots go to the same robot makers, but these four brands account for over 60% of the selections by integrators, while Fanuc alone captures 23% of the total share (see Table 6.1). After the top four suppliers, there is a significant drop-off in use of the rest of the brands. Of the 11 integrators who report exclusively using one type of robot, nine of them use Fanuc robots.

While the market is consolidated, brand exclusivity is not the norm. 33 out of 44 respondents use more than one brand. The average number of suppliers used by an individual integrator is 3.77. Some report using as many as 11 types of robots.

Table 6.1: Integrators' Use of Suppliers and Supplier Market Share

Supplier	Number of Integrators Using	Percentage
Fanuc	39	23%
ABB	24	14%
Kuka	19	11%
Yaskawa_Motoman	19	11%
Epson	11	7%
Adept_Omron	10	6%
Denso	8	5%
Universal	8	5%
Staubli	7	4%
Yamaha	4	2%
Nachi	3	2%
Kawaskaki	2	1%
Mitsubishi	2	1%
Comau	1	1%
Other	9	5%

N=44

The reasons for and implications of the high degree of non-exclusivity between integrators and robot suppliers are discussed in Chapter 5. For this chapter, the relevant issue is the breadth and variety of industrial robots used by U.S. integrators. First, the technology embedded in these robots is almost entirely foreign. Adept robots were developed in the U.S., but bought in 2015 by the Japanese company Omron (Omron, 2015). All of the other brands are designed and made in Europe or Asia (the lone exception to date is ABB, which, although Swiss headquartered, opened a robotics manufacturing plant in Michigan in 2015 [(Phillips, 2015)]). Thus, robotics systems integrators serve as the primary gatekeepers and translators of global robotics technology to US producers.

In many cases, whether an integrator uses a Fanuc or an ABB robot matters little to the functionality of the system. But it can matter a great deal on the back end because of differences in robotic programming. Robot brands not only have individual programming languages, but also different environments. For example, each brand has its own “teach pendant” which is the handheld devices used to program robots. The differences in operation are divided to some extent by geography of origin. One integrator explained it this way (note that Fanuc and Kawasaki are Japanese companies, while ABB is Swiss):

> “[An engineer’s] been trained on Fanuc. He can write the Fanuc program. If I put him on a job that had a Kawasaki robot, he'd look at it and [in] about half a day he'd say, ‘Oh, yeah, this is kind of similar’… If I put him on an ABB robot, I'll just hear questions [like] ‘Why do they do it that way? Why is this different?”

This interviewee went on to note that that his firm tries to ensure staff members know more than one language and that there is proficiency with different suppliers across the firm, echoing other interviewees.

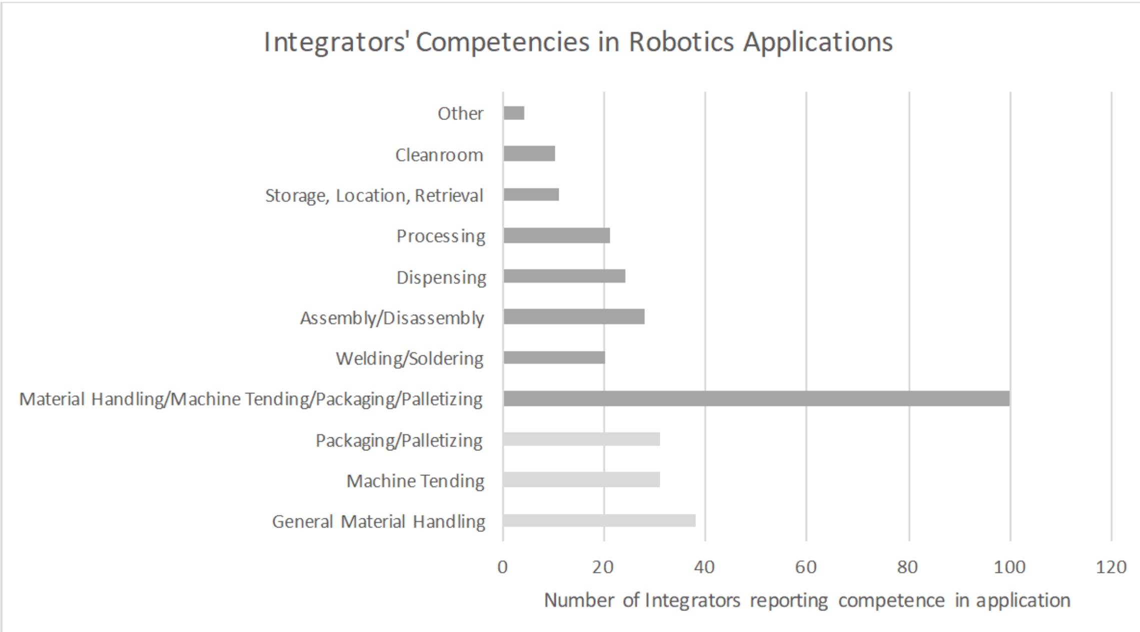
6.3. Robotics Applications

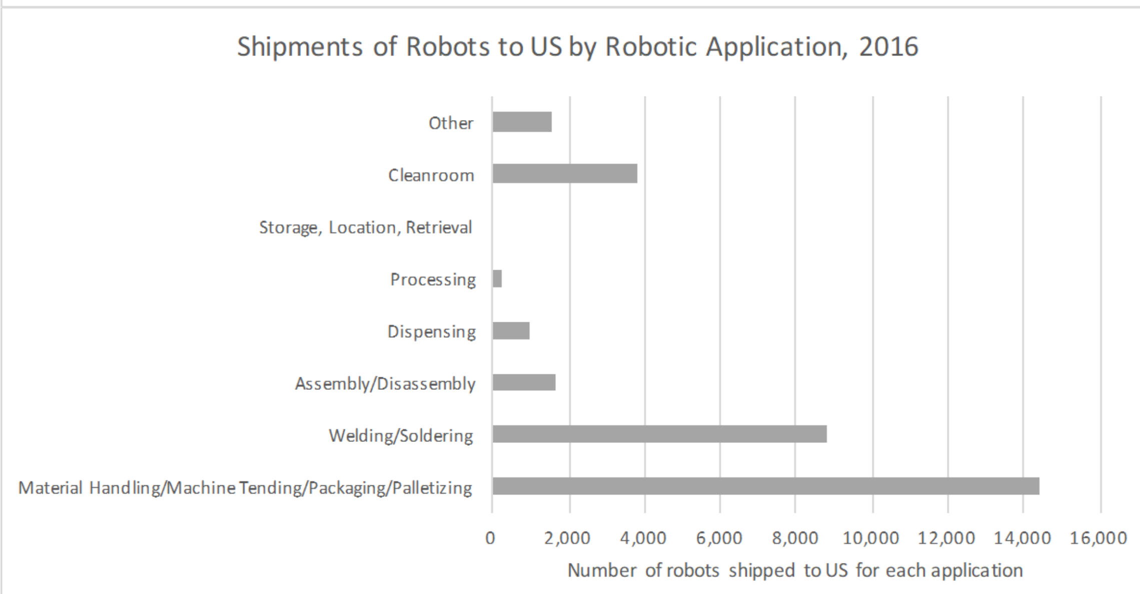
One of the advantages to using robots over other automation technologies is their flexibility. This flexibility enables them to perform a wide variety of industrial applications that traditionally had to be performed by a dedicated, single-purpose piece of machinery. Thus, robots are key components of "flexible" or "soft" automation systems because the same robot can be retooled, repositioned, or reprogrammed to perform a new task. This allows for changes in product design with minimal process disruption. In contrast "hard" automation usually consists of single-purpose components and machine tools that take considerable time to position and install, and may have to be recalibrated manually.

In practice, industrial production systems usually include features of both hard and soft automation. For small systems, little more than one or two robots and a conveyor may be necessary, enabling significant flexibility. Generally, and especially for larger systems, industrial controls provide flexibility by enabling communication between components. For a related project, I was given a tour of a robotics training facility where an item was manipulated by and passed along to robots made by several different suppliers. It was explained that while programming the individual movements of the robots was relatively easy, using controls to communicate between robots of different suppliers along the line was very difficult. Thus industrial control systems that make this communication possible, such as those made by Rockwell—also a robotics system integrator—are also key components to flexible automation. Integrators work extensively with controls and have relationships with controls suppliers. Although not the focus of this project, it should be kept in mind that industrial controls in many cases enable the flexibility of robots and thus impact the economic geography of integration.

As flexible machines, robots can perform numerous industrial tasks. The International Federation of Robotics (IFR) calls these tasks “applications,” and enumerates six broad categories and 29 sub-categories of them, not including an “unspecified” category (2017, p. 44). The choices of applications offered to survey takers were a modified version of the six broad IFR categories. The main modification in the survey is that the IFR’s “handling operations and machine tending” category was decomposed into three sub-categories, asking respondents to differentiate between machine tending (feeding material into and out of other machine tools), packaging and palletizing (handling material specifically as part of the packaging or palletizing process), or general material handling.

As expected, integrators both individually and as an industry are proficient in a wide variety of industrial applications. The average integrator has competence in five of the listed applications, and all but one respondent reported competency in two or more. Material handling is the most common of integrators’ competencies, by a significant margin (see Figure 6.1). This aligns closely with IFR 2016 shipments, which are shown below to provide context for US integrators competencies with applications. However, the remainder of the competencies diverges slightly from IFR 2016 shipment counts. While it should be kept in mind that these charts measure two different phenomena (self-reported competencies for integrators and robot shipments to the US), integrators as an industry appear to have comparable levels of competence in welding, assembly, dispensing, and processing, while the actual shipments of robots to US customers do not reflect this uniformity. After material handling, shipments of robots are highly favored towards welding and soldering.





Top Chart	Bottom Chart
• *From Survey* • *N=43* • *Respondents provided more than one answer.* • *Bottom three responses in top chart are decompositions of that category.*	• *From IFR World Robotics Report, 2017* • *Storage, Location, and Retrieval is not an industrial robotics application according to the IFR, so no statistics are provided for it.*

Figure 6.1: Integrators' Competencies in Robotics Applications vs. Shipments of Robots by Application to US

There are multiple potential reasons for this divergence. Welding systems may call for more robots than other applications, or integrators may report having varied competencies but in practice build more welding systems. Alternatively, welding may be predominantly an automotive application, meaning that integrators would be less likely to do these jobs. Also, robots are, by design, able to be repurposed from one application to another, so integrators may in some cases alter the function of existing robots without ordering new ones.

The main takeaway from the chart is that integrators have an expansive repertoire of competencies. When material handling sub-categories are decomposed into the three choices provided on the survey, integrators' portfolios appear even more expansive.

Further, when respondents were asked in a follow-up question how many of these applications are involved in a "typical integration project," the average response was 4.88, and the minimum was four (N=40). Because integrators design and build automation *systems*, they are almost always considering more than one application.

6.4. Robotics Technologies

Integrators similarly work with a variety of robotics-related technologies. Although robots are sufficiently flexible to perform the applications described above, they frequently require some type of auxiliary or embedded technology to do so. For example, a robot tasked with picking up and relocating unstandardized parts may need to be fitted with a special end-of-arm tool (EOAT) to be able to grasp the parts, as well as machine vision software to "see" them. In some cases, the technologies are less sophisticated, and do not augment a robot's performance so much as they address other common challenges to using robots. These "technologies" include managing the cables and wires attached to robots, sometimes called "robot dressing," and setting up proper safety guarding and protocols around a working robot. Although these considerations seem like afterthoughts, they have developed into important robotics sub-specialties and significantly add to the cost and complexity of operating a robot. Also included in this technology category are industrial controls, motors and drives, and motion control, which are older general purpose industrial automation technologies. For example, motion controls can be used to prevent excessive vibration in industrial systems and can be used for robots or other machinery. Robots come with motors and drives in them, but for some projects, these components may need to be reconfigured or replaced. Collaborative and mobile capabilities are emerging technologies that allow robots to work directly with humans with minimal safety equipment and to move autonomously throughout a facility, respectively.

Because these specialties associated with robotics are so widely varied, they defy straightforward classification. For the purposes of the survey they were identified as "industrial robot technologies," and integrators were asked to select the ones in which their establishment has competence—the same way they were asked about applications. The pattern of responses is also similar, with most integrators claiming to be competent in most technologies listed (see figure 6.2). The two technologies with which integrators have the least competence as an industry are mobile and collaborative robots. This is likely because they are the newest of the technologies listed, and most integrators interviewed noted that they are currently or plan on developing these competencies in-house.

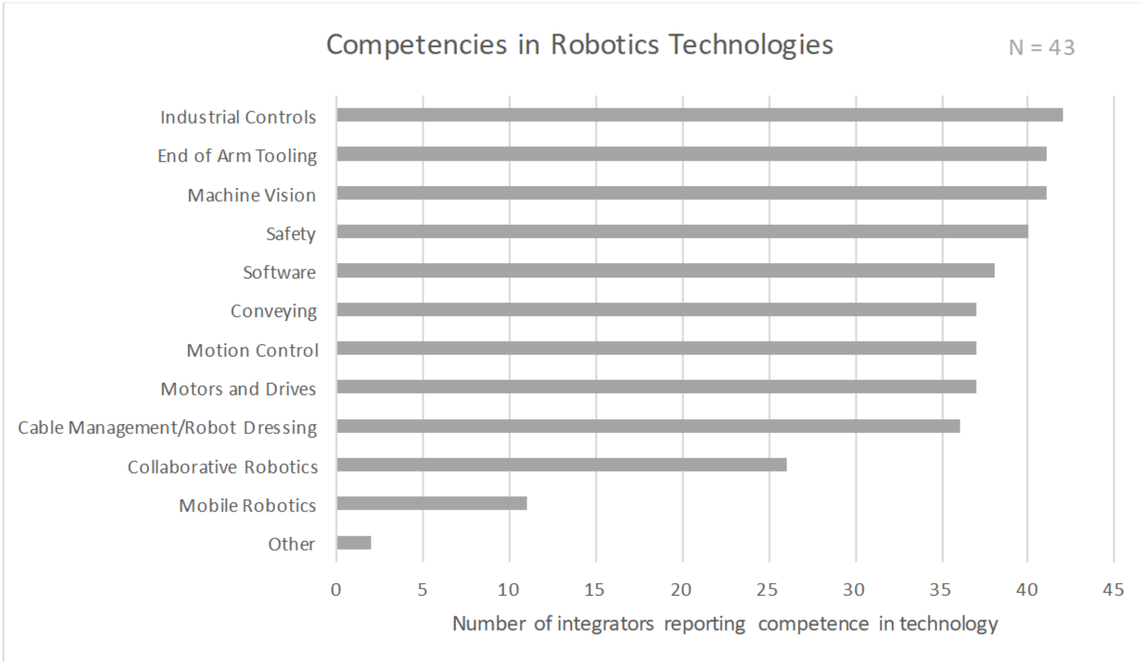


Figure 6.2: Integrators' Competencies in Robotics Technologies

The average integrator has competence in almost 9 (8.93) of the 12 listed. And again, individual integration projects are technologically complex, with an industry-wide average of almost 9 (8.88) of these technologies being involved in a typical project (N=41).

6.5. Industries Served by Integrators

The final indicator of related variety enumerated by the survey is the industry, or sector, to which integrators' customers belong. Quantifying the degree of affiliation to the same or similar industries within a geographical area has been one of the foundational approaches to measuring related variety (Boschma, 2017; Essletzbichler, 2015). However, these sector-based quantifications have not fully theorized the difference between relatedness based on product *similarity* versus that based on product *complementarity* (Boschma, 2017). As a result, they implicitly classify sectors that make similar products as more related to each other than those that make complementary products, even though in reality, those that make similar products may not be very related. For example, in a traditional sector similarity-based related variety metric, “ship and boat building” would be more closely related to “motor vehicle manufacturing” than either are to robotics systems integrators, even though in reality shipbuilders and car makers are not generally co-located and have little in common with each other except for some potential overlap in workforce, while integrators would could do business with either—and indeed do according to survey responses.

This misalignment happens because shipbuilding and auto manufacturing both belong to the North American Industrial Classification System (NAICS) code group beginning with “336” to designate transportation manufacturing, while robotics systems integrators most accurately belongs to 541330: Engineering Services. Further, the 541330 NAICS group classifies such engineering subspecialties as civil, chemical, acoustical, and traffic, who share little in terms of knowledge, technology, or clients. In fact, nonmanufacturing industries are often excluded from related variety investigations in the first place because of this classificatory ambiguity. There are ways around the industry classification problem by using other metrics for related variety such as patents and input-output tables, which have their own problems (see section 2.2). But the purpose of this survey is to produce a fine-grained sketch of exactly how one kind of inter-industry relatedness takes shape.

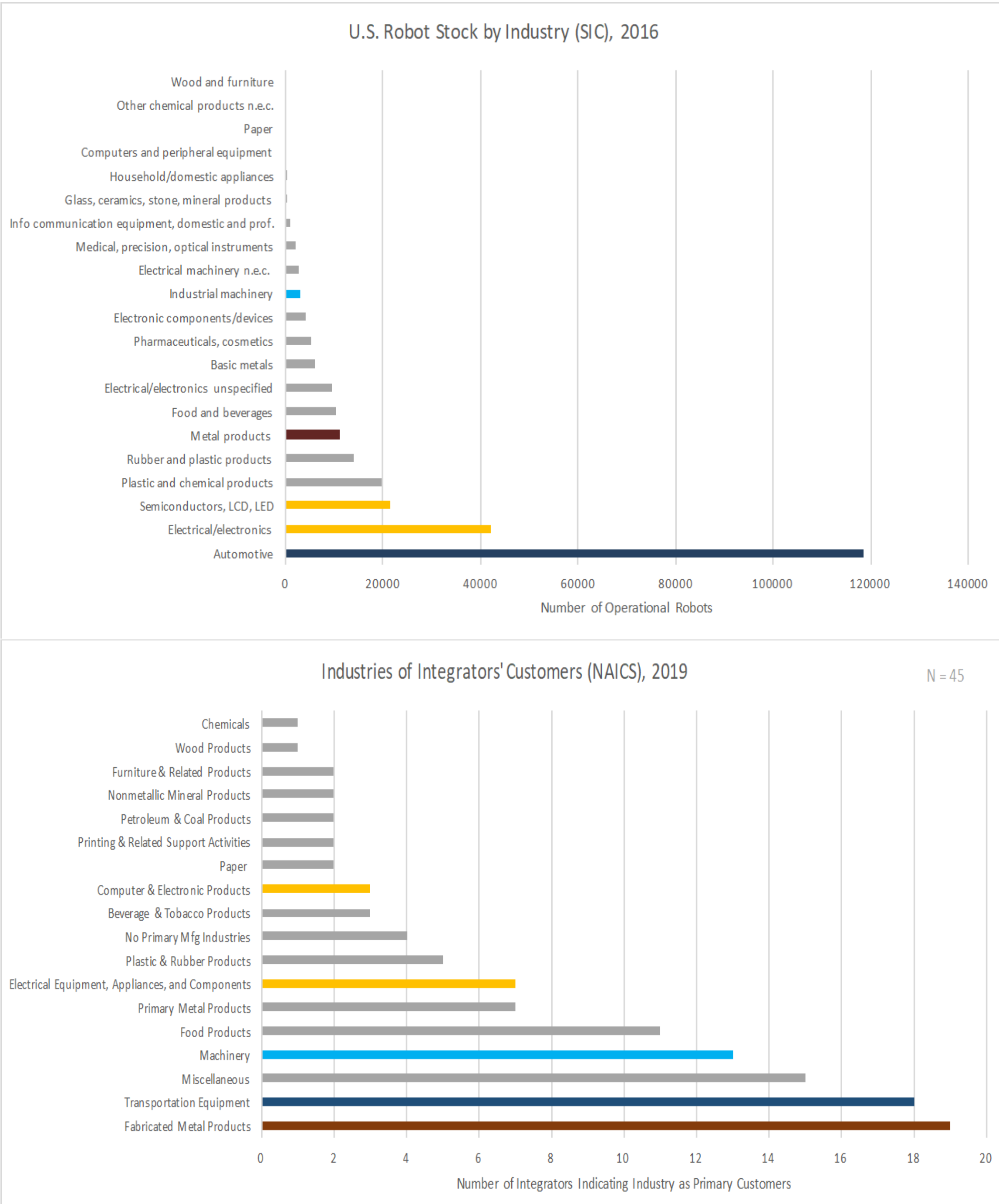
It is expected that integrators’ relationships will be limited to certain industries such as auto manufacturing, because robots have always been and continue to be most heavily used by the auto-makers. Some industries, including electrical equipment and electronics manufacturing as well as some types of metal manufacturing, have been ordering robots at a slightly faster rate than automakers worldwide since 2011, but the "robot gap" between automotive and all other industries remains large (International Federation of Robotics, 2017). In 2016, the automotive industry accounted for 50% of North America's estimated operational stock of over 285,000 industrial robots (International Federation of Robotics, 2017).

Part of this concentration in auto and durable goods-producing industries is due to robot capabilities. They are good at handling or manipulating discrete items and joining pieces of metal together. So far, other types of automation technologies or human labor are superior when working with small or delicate items or liquids.

However, these skewed robot diffusion patterns are also due to economic factors. Auto manufacturing facilities are generally very large, and larger establishments have consistently proven to be much more likely to adopt technologies than their small and medium-sized counterparts (Leigh, Lee, & Kraft, 2018). It is not surprising that robot makers initially targeted automotive companies and formed partnerships with them, typified by General Motors partnership with Fanuc in 1982 (Holusha, 1982). Robot suppliers benefit by selling larger orders of robots, and the economies of scale achieved by robotizing large plants justify the high initial investment. Even as the cost of robots has decreased, the increased likelihood of large firms to adopt robots persisted. In a nationwide survey of manufacturers administered in 2018, large establishments and automotive establishments both demonstrated significantly higher rates of robot adoption than either their small and medium-sized or non-automotive counterparts (Leigh, Kraft, & Lee, 2019).

The integrator survey does not ask integrators about the size of their customers, but it does ask what industries their customers are affiliated with. Specifically, it asks integrators which primary industries they serve, instructing them to choose up to three subsectors from the full list of three-digit NAICS codes within the manufacturing sector, and one option for the integrator to indicate that it serves no primary industry.

The distribution of primary industries served by integrators is similar to the distribution of robot stock among industries in the U.S., with durable goods in general occupying the bottom rows of the chart and nondurables at the top. However, integrators are more or less active in some industries than the distribution of robots would suggest. In particular, U.S. integrators focus heavily on the fabricated metal and machinery industries, and less so on computer and electronics and plastic and rubber, even though the former have fewer robots overall than the latter (colored bars in Figure 6.3 indicate equivalent industries).



Top Chart	Bottom Chart
• *Estimates of robot stock by industry from IFR data* • *Categorized by SIC code*	• *Industries of integrators' customers from Survey* • *Categorized by NAICS code*
• Comparable industries of interest indicated by colors • Textile and Apparel industries not included because integrators reported no customers in these categories.	

Figure 6.3: Primary Industries Served by Integrators Compared to Industrial Distribution of Operational Robot Stock in U.S

This discrepancy is not altogether surprising, because the primary industry served by an integrator is a separate question from the number of robots being used by manufacturers. As discussed earlier, large manufacturers may purchase robots directly from suppliers and not have contact with integrators. Conversely, some manufacturers may require the services of an integrator for a system with only one or two robots. Finally, there are considerable differences in production techniques *within* industries (Rigby & Essletzbichler, 2005), so robot stocks aggregated across industries should not be seen as determinant of whether an individual manufacturer within that industry uses robots.

6.6. Technological Sophistication and Competitive Strategies

The final pathway of related variety assessed by the survey is along the spectrum spanning high and low technology. One survey question gauges this by asking about integrators' perceptions of the technological sophistication of their customers. Another assesses price versus quality competitiveness, or the extent to which their customers make "high end" or "low end" products (those competing on the basis of quality would be at the high end of the market, while those competing on price would be at the low end).

Neither of these measures is an exact proxy for whether a manufacturer is "high-tech," or not—just as industry affiliation, described above, is also inexact in this regard. Manufacturers of highly precise aerospace or photonic components, whose tolerances may be microscopic, are likely both technologically sophisticated and considered "high end" manufacturers. However, high-end makers of fine furniture or apparel may compete on the cultural or symbolic significance of their products and supply chains (Scott, 2001), of which low-tech, artisanal production methods may be a part. Alternatively, common, inexpensive goods may be mass-produced by highly automated and "smart" systems, while some manufacturers in high-technology industries may be technologically behind their competitors.

Table 6.2: Technological Sophistication and Product Distinctiveness of Customers

	Less than half		**More than half**	
	Number	**Percent**	**Number**	**Percent**
Customers that are technologically sophisticated *(N=44)*	27	61%	17	39%
Customers that are high end manufacturers *(N=43)*	20	47%	23	53%

As expected, integrators' customers are close to evenly split with regard to both technological sophistication and competitiveness strategy. Customers lean slightly more towards sophistication, with roughly a 60-40 split. This is not surprising given that those seeking to add robots to their production systems are likely already operating at a high level of technological sophistication, or at least aspiring to do so. The more even 50-50 split for high end versus low end (i.e. price versus quality competition) could be reflective of the fact that the flexible nature of robots lends them to mass or custom production operations.

The reason for asking these questions on the survey is to confirm in a general sense whether integrators are exposed to a broad spectrum of production and competitiveness strategies through their customers, which would further support the idea that they are agents of variety transmission across categorical boundaries. Again, this boundary-crossing is confirmed.

6.7. Conclusion

The evidence presented in this chapter has been straightforward: integrators introduce and expand related variety along several dimensions, including technological (robotics applications, technologies, and competitiveness strategies), industrial (manufacturing sectors), and commercial (suppliers). Thus, from a relatedness perspective, integrators have the potential to relate knowledge across all of these boundaries. Viewed in concert with integrators' supply chain position and interactive problem solving and innovation strategies (see Chapter 5), integrators can be seen as cross-fertilizing agents of variety between industries, technologies, and knowledge bases.

However, the extent of related variety that flows through integrators is limited by traditional industrial dynamics and material properties. Despite being a relatively new industry, robotics market share is concentrated among a few suppliers. While the high probability that integrators will have to work with one of the top four brands encourages them to be competent with some or all of their operating systems, it also limits their chances of working with other types of robots and exploring potentially new capabilities. Integrators also have limited penetration into chemicals, petroleum, nonmetallic minerals, and textiles in part because of the small margins and inexpensive labor in some of these industries, but also because of the reality that robots are not as well suited for fluids and soft materials—especially in large quantities—as they are with discrete, solid objects.

Although integrators' ties to some industries and suppliers are stronger than others, as a community they have at least some contact with nearly all suppliers and industries, and individually, most integrators strategically seek to expand these affiliations. By constantly learning, expanding their technological competencies, and re-applying this knowledge and these competencies to new problems for new customers, integrators increase heterogeneity in industries and industry clusters (Rigby & Essletzbichler, 2005). By introducing variety into industrial ecosystems, the integration process positions these ecosystems to select from those elements that best enable adaptation and prevent lock-in.

CHAPTER 7

HUMAN CAPITAL IN ROBOTICS SYSTEMS INTEGRATION

7.1. Introduction

The emphasis on incremental, interactive innovation in robotics systems integration influences its human resources practices. Integrators seek to recruit and cultivate a workforce that can thrive in this type of innovative environment, with frequent, project-based demands. In Chapter 2, the knowledge required of integrators was described as "synthetic," meaning that is acquired by tacit and experiential or "learning by doing" processes. While this characterization remains true, it runs the risk of excluding systems integration from the larger regional innovation systems conversation, because it perpetuates a reductive view of innovation. This reductive view emphasizes and privileges innovative activity that results in patentable, often radical developments in science and technology, usually also intended for mass commercialization. It relies on highly trained personnel with master's or doctoral degrees in the sciences or engineering. This emphasis minimizes the role of so-called "low-tech" incremental advances—the kind that integrators make routinely as they improve industrial production systems—in regional innovation systems (Bender & Laestadius, 2005; Hansen, 2010; Laestadius, 1998; Patel & Pavitt, 1994).

If robotics systems integration and other similar industries are to be included in discussions of regional innovation systems and related policy, a richer classification of the kinds of human capital emphasized is necessary (Asheim et al., 2011). This chapter works towards this reclassification by critically examining the conceptualization of human capital in disciplines that analyze it as an aggregate phenomenon determining the economic trajectories of cities, labor markets, nations, or industries. These disciplines include economics, economic geography, and urban and regional planning.

The chapter proceeds as follows: first, it critically reviews the operationalization of human capital in disciplines that are concerned with urban and regional economies. It argues that while to date the idea of human capital—as well as one of its subcategories, knowledge—has been reductively conceptualized, there are additional dimensions of human innovative endeavor that can be incorporated into theoretical and empirical assessments of human capital, and that these dimensions define a synthetic knowledge base.

Next, the chapter describes an approach to human capital measurement used by disciplines concerned more with human capital at the individual and organizational levels and suggests that incorporating elements of this approach—specifically the assessment of "knowledge, skills, abilities, and other characteristics"—could benefit the study of urban and regional economies by more closely representing the value of synthetic-dominant work and industries.

Finally, the chapter describes how this individual and organizational approach to measuring human capital was implemented in the survey and interviews and interprets the results of this implementation. It is suggested that a *synthetic sensibility*, or a predilection towards solving practical and material problems, often in teams, is an important component of human capital for robotics systems integrators and related businesses.

7.2. Broadening the Definition of Human Capital in Regional Innovation Systems: Considering Knowledge, Skills, Abilities, and Other Characteristics (KSAOs) at Multiple Scales

Goldin (2016) defines human capital as "the stock of productive skills, talents, health, and expertise of the labor force" (p. 83). This definition is itself broad, and is also broadly shared by economists, geographers, and economic development planners. Although this conceptualization of human capital is multi-dimensional, only a narrow set of these dimensions has traditionally been measured. Moreover, this measurement has often been achieved by traditional indicators of accumulated knowledge, such as education levels, occupational and industrial mixes, and patent activity.

While these indicators have been robust predictors of both individual and aggregate economic growth, they are the revealed results of human capital and not necessarily reflective of the underlying qualities that drive economic productivity. For example, while a biomedical researcher needs a high level of education as well as employment in a university or corporate research lab to develop a lifesaving drug, she likely will not actually make such a valuable breakthrough without personal curiosity, drive, and discipline. Likewise, a heating, ventilation, and air conditioning technician may possess similar levels of curiosity, drive, and discipline, but may not have had the same education and employment opportunities as the researcher. While education and prestigious jobs are themselves indicators of human capital, the direction of causality becomes muddled at some point along the way.

What are the relative contributions of innate or environmentally acquired predilections versus opportunity and training to biomedical breakthroughs? To date, we have considerable amounts of data on the latter, but few on the former. There is no large dataset of exactly how people generate ideas, solve problems, or develop skills. To deepen the economic perspective on human capital, I borrow the concepts of *attributes and other characteristics* often used in human resources assessments, and operationalize it in the survey of integrators.

7.2.1. Macro and Micro Approaches to Human Capital in the Social Sciences

Within the social sciences, there are two major approaches to studying human capital: the macro approach to human capital (MaHC) and the micro approach to human capital (MiHC). MaHC is used by the disciplines listed above (economic geography, etc.), with the unit of analysis being cities, states, nations, industries, or occupations (sometimes economists use the individual as the unit of analysis, but they often use large sample sizes to enable substantial generalizations). MaHC is concerned with how individual and organizational human capital scales up to enhance competitiveness at these comprehensive levels.

MiHC analyses are at the individual and organizational levels. These disciplines include industrial/organizational studies, business strategy, management, human resources, sociology, and psychology. Sometimes these inquiries include very large companies, but MiHC rarely explores human capital at spatial or industrial scales.

This study takes a MaHC approach, because it is directly concerned with human capital at industrial and regional levels. However, it borrows from MiHC in its research design in order to create a human capital construct that is more appropriate for the industry in question.

7.2.2. Problems with the Macro Approach to Human Capital

The traditional way that disciplines concerned with the spatial distribution of human capital—MaHC as they are called here—have measured human capital entails two fallacies.

The first is a *misspecification fallacy*, because it ignores all of the possible dimensions of human capital found in the literature concerned with the concept at individual and organizational levels (Ployhart & Moliterno, 2011; Rousseau, 1985). These are often called "knowledge, skills, abilities, and other characteristics" (KSAOs) in organizational studies and human resources literature (Ployhart & Moliterno, 2011; Schmitt & Chan, 1998).

The second fallacy is a *cross-level fallacy*, because it assumes geographically aggregated measures of human capital adequately represent those at organizational and individual levels (Ployhart & Moliterno, 2011; Rousseau, 1985). This problem generally results from scaling up from individual measures of human capital to spatially aggregated scores of human capital.

This chapter addresses the misspecification fallacy empirically by incorporating “abilities” and “other characteristics” into an assessment of robotics systems integrators’ human capital needs. It then discusses how this richer specification of human capital can better inform economic development efforts at local, regional, or industrial scales.

7.2.2a. The Misspecification Fallacy of Human Capital Measurement

Becker’s pioneering work defines human capital by how investments are made. “Activities that influence future monetary and psychic income by increasing resources in people” (Becker, 2009, p. 11) are what Becker calls investments in human capital. Despite acknowledging that many such kinds of investments can be made—formal, informal, individual, public, etc.—he relies almost solely on education as the primary indicator of investment. This is for good reason: consistent measurements of education over time were widely available and understudied at the time, as economists until then were primarily concerned with quantifying returns to investments in physical capital (Becker, 2009).

However, the tradition of measuring human capital by way of education has become relatively ingrained. As Rauch (1993) puts it,

> “In the empirical labor economics literature, the human capital that an individual accumulates over her lifetime is typically decomposed into two measureable components: education and experience, measured by years of schooling completed and age minus years of schooling minus six, respectively” (p. 386).

Education serves as the primary proxy for human capital, while “experience” represents difficult-to-measure skills and competencies acquired on the job. In some of the most widely cited papers on the topic, this formulation has come to be shortened into the catch-all idea of "skills" (Glaeser & Mare, 1994; Glaeser, Saiz, Burtless, & Strange, 2004).

Florida's "Creative Class" framework (Florida, 2002b, 2002c) though not without controversy (see below)—marked a major shift in thinking about human capital in urban and regional contexts by suggesting that it should more specifically be thought of as creative talent rather than an accumulation of education and work experience.

Although not a radical departure from the classic "education and experience" formulation of human capital, the creative class correction to the misspecification of human capital is to add a variable representing a concentration of occupational groups thought to be especially creative (Florida, 2002b). These groups, "professional and technical workers" and "scientists and engineers," as defined by the U.S. Bureau of Labor Statistics' standard occupational classifications (SOC), are suggested by Florida as being especially responsible for the creative output cities need to maintain competitive advantage in the 21st century knowledge economy. Florida calls this measure the "talent index," and it has been criticized for amounting to a more stylized version of what was already known about urban knowledge agglomeration (Donegan & Lowe, 2008; Glaeser, 2005), and also for confusing artistic creativity with the kinds of creativity used in analytical problem solving (Liu & Grusky, 2013).

Despite these criticisms, it coincided with significant interest among urban planners and economic geographers in the occupational and industrial structures of cities and regions (Barbour & Markusen, 2007; Feser, 2003; Koo, 2005). These investigations presume that by looking at the tasks people predominantly perform (by way of occupations) and the products and services that people predominantly produce (by way of industries), we can infer information about a city's or region's level of human capital over and above what a traditional measurement of its average level of education and work experience would permit. This approach presumes that, in addition to having certain overall levels of human capital, fit and specialization are also important.

The creative class concept also adds an element of human capital not based on knowledge called "tolerance." According to Florida, tolerance indicates an openness to new ideas and experiences, which aids in the creation of novel, productive economic activity (2002). Tolerance is measured by a gay index (Florida, 2002b) and sometimes also a "bohemian" index (Florida, Mellander, & Stolarick, 2008). The gay index is the concentration of households in which a householder and an unmarried partner were of the same sex (before same-sex marriage became legal in the U.S.) (Florida, 2002b), and the bohemian index is the concentration of residents whose primary occupations are in various visual or performing arts or design (Florida, 2002a). These metrics can reasonably be expected to be correlated with tolerance at a metropolitan level, but the gay index measures the existence of same-sex households rather than peoples' tolerance for them, and the bohemian index indicates *revealed* bohemian sensibilities through a hand-picked set of occupations. These metrics add to the richness of human capital measures, but are still incomplete.

To date, the best way to convert regional industry or occupation structure to human capital is by using the Occupational Information Network (O*NET), which is a database that maps skills, knowledge, and abilities, to occupations (Liu & Grusky, 2013; Scott, 2008). Although creation of the O*NET database involved thorough research into the working conditions, skills, knowledge areas, and abilities of an extensive list of occupations (O'NET, 2019), it lacks geographic specificity because the occupational profiles it generates are nationally generalized.

Economic geographers can use O*NET data to assess regional differences across multiple levels of human capital, such as social or physical skills, but observed differences are only reflections of underlying occupational structures. For example, if O*NET data are used to determine that places with high concentrations of cognitive and social skills are more resistant to recession-driven unemployment, as Weinstein and Patrick (2019) do, it is no different than saying that places with high concentrations of *occupations that rely on* cognitive and social skills are more resistant to recession-driven unemployment, because the skills are directly mapped onto the occupations, and they are constant across space. In O*NET, welders in Ohio working in an auto factory have exactly the same skill profile as welders in Mississippi working at a shipyard, even though in practice, their work varies greatly.

7.2.2b. The Cross-level Fallacy of Human Capital Measurement

A close reading of the previous sections shows that what began as a misspecification fallacy made a subtle move from the individual to the region to become a cross-level fallacy. Without much examination, it was assumed that if more education and work experience is good for individuals, it must also be good for cities and regions (Glaeser, 2011; Moretti, 2012). The “more traditional human capital is better” framework posits that the self-reinforcing spatial accumulation—referred to as “agglomeration” in urban economics—of highly educated individuals is a fundamental law of economics.

In Florida’s formulation, the traditional human capital construct of aggregate education levels does play a role, but it is not the only ingredient. Rather, the maximization of creative talent across a city or region requires a more holistic creative milieu, consisting of cultural attitudes and amenities to which creative workers are drawn and which nourish their creative spirit. However, the creative class perspective remains essentially a “more traditional human capital is better” framework because these auxiliary aspects of creativity are necessary only insofar as they enhance the creativity of highly educated workers of specifically defined creative occupations.

This raises the question of whether human capital is in fact linearly related to regional prosperity. With so many elements of human capital missing in these measurements, it may be a combination of education, tolerance, and other unrevealed qualities of the workforce that truly make for a prosperous place. Human resources managers know that the best organizations are made up of people who have complementary rather than competing skills, abilities, and interests. Can cities be thought of as analogues to organizations in this sense? Might there be diminishing returns to education-dominant measures of human capital at a certain point?

Another question the "more is better" framework raises is whether it results in fair policies. Superficially, this might not matter to MaHC scientists if they are only concerned with aggregate outcomes at the level of a city or a region. But these disciplines and professions are increasingly becoming concerned with growing levels of inequitable growth (Chetty, Hendren, Kline, & Saez, 2014; Piketty, 2015). While cities may benefit in the short term from attracting as many educated residents as possible, this strategy may not lead to sustained growth. There is evidence that highly innovative cities are more unequal than their less innovative counterparts (Breau, Kogler, & Bolton, 2014) and that the presence of high-technology industries can be associated with some increases in employment and wages for workers (which could be mitigated by rising costs of living), but not a reduction in poverty (Lee & Rodríguez-Pose, 2016). Moreover, high-tech human capital recruitment strategies pit cities and regions against each other in entrepreneurial knowledge-attraction competitions that divert public funds away from long-term community investments in areas like education or infrastructure (Peck, 2005).

The MaHC policy "takeaway" almost always depends upon generating infusions of high-tech, creative, or knowledge-intensive jobs. Besides being difficult to implement from a policy perspective, this strategy incorrectly assumes that human capital is ahistorical (Goldin, 2016). Regions may be endowed with human capital legacies from agricultural or industrial knowledge passed down through generations. While these industries may not be salvageable, the skills used in them could be repurposed, without necessarily starting from scratch in the race for talent. But MaHC researchers, forced to rely on the same education, occupation, and industry data for roughly the last half-century, have little recourse to determine what they might be missing or what alternative combinations of human capital might be optimal.

7.3. Learning from Micro Approaches to Human Capital: Incorporating KSAOs in Human Capital Research

MiHC scientists, who examine human capital from an organizational perspective, use a multi-dimensional construct of human capital called "Knowledge, Skills, Abilities, and Other Characteristics" (KSAOs). KSAOs originate at the level of the individual and scale up to form "human capital resources" for an organization (Ployhart, Nyberg, Reilly, & Maltarich, 2014). Schmitt and Chan (1998) define KSAOs as follows:

> "*Knowledge* refers to the foundation upon which abilities and skills are built; it involves an organized body of information—usually facts, rules, and procedures—that, if used, makes good job performance possible. *Skills* refers to the capability to perform tasks with ease and precision. Most often they involve psychomotor-type activities that people perform using body movements, arms and hands, vision, and so on. *Abilities* usually refers to the cognitive capabilities necessary to perform a job function; these often require the application of some knowledge base…[*Other characteristics*] are personality traits that may be helpful for the performance of certain tasks (e.g., persistence, tolerance of others' viewpoints)" (p. 46, italics original except for last instance).

Detailed KSAO assessments are used by human resource managers in selecting personnel for specific positions or organizations (Schmitt & Chan, 1998), so they are not practical for measuring human capital at larger scales. Human resources scholars themselves are trying to understand how individual KSAO profiles scale to the organizational level (Nyberg, Moliterno, Hale, & Lepak, 2012; Ployhart & Moliterno, 2011; Ployhart et al., 2014).

The purpose in borrowing from KSAOs is not to convince economic geographers to recreate them in their assessments of place-based human capital, but rather to demonstrate that there are additional and alternative dimensions of human capital that have not been explored. Only rarely do MaHC researchers attempt to measure "other characteristics," an exception being Florida's aforementioned tolerance index, which is still subordinate to more traditional knowledge and talent measures.

Along with testing numerous human resources and recruiting patterns and practices of integrators, this survey operationalizes an extensive battery of 14 KSAOs to test their overall and relative importance. The aim is to deepen our understanding of human capital needs beyond education levels and knowledge bases to find ways to make synthetic knowledge-dominant industries and places relevant in contemporary human capital strategies.

The remainder of the chapter answers Research Question 2 and its subquestions by reporting and analyzing survey and interview results. It begins by discussing integrator workforce composition and recruitment practices (Section 7.4), and then moves on to the KSAO component of the survey (Section 7.5), followed by a discussion of the results (Section 7.6).

7.4. Survey results and interpretation

7.4.1. Workforce Composition

Engineers with four-year degrees play key roles within integrator firms, performing core integration functions and also often filling sales roles. But integrators also recruit and employ workers from a variety of occupational and educational backgrounds. Most notably, technicians and other workers with two-year degrees or other credentials from technical schools or community colleges are central to integrators' human resources recruitment and practices.

While engineers (likely with bachelor's degrees, but not always) make up 38% of the average integrators' staff, technical and production workers comprise another quarter and sixth, respectively, adding up to another 37% in non-degreed technical workers. This technical staff has varied functions in integrator establishments, but their primary jobs are to work with engineers to build and test robotics automation systems. In some cases, a crew of engineers and technicians travels with a system to set it up and commission it at the customer's site, although in cases where travel is costly, local crews are hired for the installation. While the survey did not ask respondents to further disaggregate engineers and technicians into subfields and disciplines, interviewees report that electrical and mechanical engineers are the main disciplines they draw from, and electricians provide much of the technical work. This is not to suggest that integrators exclusively look within these fields, as they regularly recruit people with a wide variety of related industrial and engineering skills.

Table 7.1: Composition of Integrator Staff by Job Category

Job Category	Percentage of Staff (Average)
Engineers (not including sales engineers)	37.8
Technicians (i.e. fabricators, installers, electricians)	25.0
Laborers/Production Workers	12.3
Scientists (professionals with non-engineering degrees)	1.0
Salespeople and Sales Engineers	9.8
Administrative and Clerical Workers	11.0
Trainers	0.5
Other	2.8
Total	100

N = 44
Categories displayed in table exactly as they appeared in survey

The heavy reliance on engineers, technicians, and production workers, and the almost non-existent role for scientists reinforces the supposition that integrators work from a synthetic, as opposed to analytical, knowledge base.

7.4.2. Recruitment of Entry-level staff

This staff composition is also reflected in integrators' recruitment efforts. The survey asked integrators to identify sources from which they hire entry-level integrators. The question listed seven sources (see Table 7.2), and instructed respondents to select all sources that apply. Most integrators selected multiple sources: 41 integrators answered the question by selecting 126 total choices, meaning that respondents on average selected three of the choices as hiring sources they commonly use.

Table 7.2: Entry-Level Recruitment Sources of Integrators

Type of Institution		Number of Integrators
4-year Post-Secondary	Local (within 100 miles)	28
	Regional (within 5-state area)	17
	National	14
	At Least One 4-year Institution	35
Sub-4-year Post-Secondary	Community Colleges	25
	Trade, Vocational, or Technical Schools	27
	At Least One 2-year Institution	30
Secondary	High Schools	12

N=41
3 respondents selected "other" category

The most common individual entry-level hiring source identified by integrators is local four-year universities, with community colleges and trade, vocational, or technical schools close behind.

The table also aggregates choices into more general categories. First, it combines the selections into four-year postsecondary categories (local colleges and universities, regional colleges and universities, and national colleges and universities), and sub-four-year postsecondary categories (Community colleges and trade, vocational, and technical schools). The table shows the number of integrators that selected at least one choice in either of the two categories (note that those that selected more than one choice in either of the categories are only counted once). Thirty-five integrators source entry-level candidates from at least one four-year option, and 30 source candidates from at least one sub-four-year option (not including high school). Twenty-six of the 41 (63%) respondents source candidates from both categories (not shown), while only nine source exclusively from four-year pathways and four source exclusively from sub-four-year categories (not shown). While integrators lean toward four-year colleges for recruitment, they remain heavily reliant on all types of postsecondary education options to sustain competitiveness.

It is also likely that integrators are not resorting to recruiting candidates from less prestigious institutions out of necessity. When asked to identify which of the seven choices provides the *best* candidates, about two thirds of respondents who answered this question chose colleges and universities, while another one-third chose shorter technical and professional options (Table 7.3). Thus, technical schools and community colleges are not simply backstops where integrators go for satisfactory candidates in tight labor markets. In fact, many integrators find superior talent in these institutions.

Table 7.3: Best Entry Level Hiring Sources

4-year Post-Secondary	Local (within 100 miles)	9
	Regional (within 5-state area)	3
	National	6
	Total 4-year Institutions	18
Sub-4-year Post-Secondary	Community Colleges	5
	Trade, Vocational, or Technical Schools	6
	Total Sub-4-year Institutions	11

N=29
No respondents identified candidates from high schools as best.

The emerging pattern of human capital needs in robotics systems integration is that while bachelor's degree-level engineers make up an approximate plurality of the integrator workforce, integrators are also heavily reliant on technicians and tradespeople. The fact that over a third of reporting integrators hire their *best* candidates from sub-four-year institutions suggests that they recruit there voluntarily and are not forced to do so because of insufficient supply coming out of colleges and universities. Even high schools, though not the preferred places for recruitment, do produce qualified candidates, with nearly 30% (12 out of 41) of integrators recruiting at high schools.

Overall, it remains difficult in general for integrators to find entry-level candidates (although not nearly as difficult as finding mid- or senior-level employees, which will be discussed later). Sixty-four percent of respondents said it was either "somewhat difficult" or "extremely difficult" to hire entry-level employees, while only 36% said it was "somewhat easy" or "neither easy nor difficult." With such a small sample size, it is not apparent whether specific locations or hiring sources are associated with difficulties in hiring. Of those reporting hiring difficulties, the most common reason (16 respondents) was that applicants "do not have sufficient technical or professional skills," while another seven indicated that there were simply not enough applicants. It should also be noted that the national unemployment rate remained below 3.8% during the time the survey was administered and was below 4% for most of the prior year (United States Bureau of Labor Statistics, 2019), so hiring difficulties were a widespread problem for employers at the time.

Interviews shed some light on the nature of these hiring difficulties by suggesting that it is not a particular domain of knowledge or specific skill that candidates lack, but rather the inability to apply their knowledge and skills to practical, project-based problems. Some integrators blame four-year engineering programs for emphasizing theory too heavily over the practice of engineering.

This hiring pattern has two economic development implications. One is that despite the emphasis on attracting or producing college-educated populations as a universally applicable economic development strategy, as often suggested by the Macro approach to Human Capital, places with high concentrations of integrators and other similar businesses (e.g. other types of engineering consultants and manufacturers) need both college-educated *and* technically trained workers. In other words, specific organizational human capital needs of integrators in this case do not scale up to the generalized MaHC finding that more education is always better.

The other implication for local economies is that local educational pipelines for synthetic knowledge-based industries are extremely important. Out of the total 126 hiring source selections made by survey respondents, 92 of them (73%) were predominantly local-serving institutions. These include local colleges and universities, community colleges, trade, vocational, and technical schools, and high schools. Regional colleges and universities are not counted as "local" here, although in rural places where the nearest four-year institution is more than 100 miles away, they may effectively function as the "local" university. A comprehensive educational ecosystem, including strong high schools, robust technical and trade programs, and colleges and universities with strong applied engineering programs are essential to maintaining the competitiveness of integrators. To the extent that integrators are representative of other synthetic, industrial, or "low-tech" industries, such an education system would also help to maintain the competitiveness of industrial economies.

7.4.3. Recruitment of Senior Staff

Integrators report having much more difficulty in hiring mid-level or senior employees than they do for entry-level employees. While finding seasoned and competent employees is a challenge in many industries, it does appear particularly acute in robotics systems integration. Ninety-three percent of integrators report that it is either somewhat or extremely difficult to find experienced workers. None report that it is easy.

Integrators spread searches relatively evenly among potential sources of experienced employees (see table 7.4). Even though some interviewees expressed reluctance to recruit employees from customers, nine survey respondents appear willing to do so. Hiring from other systems integrators appears to be the most promising way of finding quality mid- and senior-level employees. Most integrators (17 out of 26; not shown in table) say that other integrators are the best source of experienced employees. Further, ten of these 17 integrators indicated that their best candidates come from other integrators located farther than 100 miles away, suggesting that either a reluctance to poach from nearby competitors, insufficient local integrator labor markets, or some combination of both. This result is arguably statistically different based on region. A Chi-square test suggests that integrators outside of the ENC Census division are statistically more likely to hire senior-level employees from integrators farther than 100 miles away (p = 0.091), if a 90% significance threshold is used. This result suggests that "rust belt" integrators have a geographic advantage by having a more proximate stock of experienced integrator personnel nearby.

Table 7.4: Hiring Sources for Senior Staff

Other integrators (within 100 miles)	Other integrators (farther than 100 miles)	Manufacturers (customers)	Manufacturers (not customers)	Robotics or Automation Suppliers	Other Sources
21	20	9	18	17	24

N=45

Nevertheless, there is general difficulty in recruiting experienced integrator employees. As a result, integrators invest heavily in internal talent development. One Ohio integrator's comment illustrates this challenge:

> "For a [robot tech] to be effective you may have a good mechanical person or a person who really understands logic. But you're going to have to send them to a robot school as well as hands-on training, where you tag them up with a more experienced programmer or technician. And it's expensive when you have somebody out three to four weeks of training in various robot companies. A week in Detroit is not necessarily cheap…so you're investing in the employees. And you're not always going to find somebody that comes in and can program on three different robot systems and has either a welding background or a machine background, or understands the safety. And we recently did a training section with an RIA safety certification trainer where we ran everybody through all the RIA ANSI standards and how to build cells properly, how to do risk assessments and things like that. So you have a huge investment in your staff and even somebody straight out of college isn't going to know what you need. If you steal somebody from another integrator with 14, 15 years experience, you're paying top-of-the-line money for them."

Experienced integrators have accumulated exposure to a broad set of integration problems (multiple robotic programming languages, welding and machining, and safety practices) and a specific sequence of supplier- and industry-supplied trainings that generally only current integrator employees have access to. Integrators tend to understand that secondary and postsecondary institutions do not—and probably cannot—provide such a thorough set of skills to students.

7.5. KSAOs in Robotics Systems Integration and other Industries that are Synthetic Knowledge-dominant

7.5.1. Introduction

This survey uses a "Knowledge, Skills, Abilities, and Other Attributes" (KSAO) model and traditional questions about workforce composition and recruitment to assess the human capital characteristics of integrators. The results are intended to have limited generalizability to other synthetic and low-to-medium tech businesses like manufacturers and related service providers.

There is no benchmark against which to gauge responses to these questions. For example, there is no established minimum percentage of an industry performing technical occupations that would define a synthetic knowledge base (Research Question 2a). Nor is there a specific level of importance of on-the-job experience that separates a synthetic knowledge base from an analytical one. The survey data are presented here to begin the work of empirically defining—and not simply assuming—a synthetic knowledge base within an industry.

Thus, these data begin to build a general set of knowledge, skills, abilities and other characteristics that are important to integrators (and by extension other synthetic knowledge base industries) so that they can be further studied.

They also allow for comment on policy and workforce development issues. For example, the KSAOs test the relative importance of applied robotics and automation skills, represented by "prior robotics training" and "industrial automation skills (not including robotics)," versus the more theoretical "knowledge of artificial intelligence concepts and applications" that drive robotics research and development. This test not only further confirm the status of robotics integration as a synthetic (as opposed to analytic) industry, but also brings to light a distinction between, on the one hand, the work involved in developing and advancing new robotics technology, and on the other, applying these new advances to practical problems. These two types of work take place at different places along the supply chain and are concentrated in different geographies.

Finally, these human capital data on integrators permits an assessment of whether there is a "skills gap" or "skills shortage" for employers working in applied robotics. While some prominent reports (e.g. Deloitte Development LLC, 2011) claim that U.S. manufacturing is held back by a workforce insufficiently skilled in working with 21st century technology such as robots, others have critiqued this characterization, suggesting that these skills gaps or shortages are localized and idiosyncratic (Weaver & Osterman, 2017) or easily remedied by on-the-job training (Cappelli, 2014). In other words, is it more important for potential systems integrator employees to show up for work on the first day with an extensive suite of robot programming languages and industrial controls knowledge at the ready, or simply to demonstrate an interest in and aptitude for learning these skills while on the job? The data suggest the latter is true, but also do not rule out the potential benefits of increasing offerings of skill development in robotics and industrial automation.

7.5.2. Design of the KSAO Survey Element

As displayed on the survey, this section contained two separate lists of seven items each, and asked respondents to rate each item according to how important it is in "making a successful robotics systems integrator employee." For the purposes of answering the research questions, there was no reason to break up these 14 items into two separate questions. However, a 14-point matrix would create a significant cognitive burden for a survey taker, so it was divided into two categories—one asking about "characteristics" and the other about "skills or knowledge."

For research purposes, these questions are designed to measure the KSAOs demanded by integrators and to be able to generalize them to a synthetic (as opposed to analytical or general) knowledge base. Table 7.5 lists each question, or construct, and the type of KSAO or Knowledge Base it was designed to represent.

Table 7.5: KSAOs and Knowledge Bases as Operationalized in Survey

Item	**KSAO**	**Knowledge Base**
Mechanical Aptitude	Ability	Synthetic
Interest in Working With Hands	Other characteristic	Synthetic
Interest in "Tinkering" with things	Other characteristic	Synthetic
Creativity	Ability	General
Personal experience with industry or manufacturing	Other characteristic	Synthetic
Ability to complete repetitive or routine tasks	Ability	General
Interest in solving new problems	Other characteristic	General
Prior robotics training	Skill	Synthetic
Industrial automation skills (not including robotics)	Skill	Synthetic
Proficiency in artificial intelligence concepts and applications	Skill	Analytical
Ability to memorize lots of information	Ability	General
Computer/software programming	Skill	Analytical/Synthetic
Scientific research	Skill	Analytical
General communication skills	Ability	General

There are several caveats and limitations to this list. First, it is not an exhaustive list of knowledge, skills, abilities, and other characteristics that integrators may look for when making hiring decisions. Based on background research into the industry, these items were chosen as the most important. Unlike some surveys of manufacturers (e.g. Leigh et al., 2019; Weaver & Osterman, 2017), this survey did not ask about basic reading and math skills. This question was omitted because although robotics systems integration shares similarities with manufacturing, it was apparent from background research that so-called "unskilled labor" in which basic competencies may be in question is not a segment of the labor market searched by integrators.

The list is also not evenly divided on the basis of KSAOs or Knowledge Bases. The priority in designing the survey was to create a list of items that would be meaningful to integrators; whether they fit neatly into human capital categories was of secondary importance. This is accounted for in the analysis of these responses by comparing their relative importance individually and not, for example, making generalizations such as "abilities are more important than skills." Lastly, the categorizations in Table 7.5 may be disputed, because the definitions of the individual KSAOs given above are vague. For example, "proficiency in artificial intelligence concepts and applications" could be interpreted as knowledge rather than skill, but the question here was phrased to imply that the capacity to apply the knowledge, rather than the knowledge itself, is the issue at hand. Likewise, "proficiency in artificial intelligence concepts and applications" could fit in either the analytical or the synthetic category. Here I consider it analytical because I hypothesize that it is of relatively little importance in applied robotics as opposed to work that takes place farther up the supply chain, where these concepts are built into robots in research and development labs. In fact, no "knowledge" KSAOs are even included in the list, because prior survey questions about education and recruitment captured the "knowledge" element of human capital as it is typically constructed. As advocates of using KSAOs note, the precise distinctions between the various KSAOs is not of crucial importance; rather, it is the "notion that each type of human characteristic should be considered in the generation of a comprehensive list of capabilities" (Schmitt and Chan, p.46).

7.5.3. Integrator KSAO Results

The questions ask respondents to rate the importance of each item on a scale from one to three, where three corresponds to "very important," two to "somewhat important," and one to "not important." The list of attributes ranked by average importance score judged to make a successful integrator is shown in Table 7.6.

Table 7.6. Results of KSAO Element on Survey

Item	Mean	Mode	Standard Deviation	KSAO	Knowledge Base
Interest in solving new problems	2.91	3	0.35	Other characteristic	General
Mechanical aptitude	2.87	3	0.40	Ability	Synthetic
General communication skills	2.69	3	0.46	Ability	General
Interest in working with hands	2.61	3	0.61	Other characteristic	Synthetic
Creativity	2.53	3	0.54	Ability	General
Industrial automation skills (not including robotics)	2.51	3	0.50	Skill	Synthetic
Interest in "tinkering" with things	2.49	3	0.65	Other characteristic	Synthetic
Computer/software programming	2.36	2	0.60	Skill	Analytical/Synthetic
Personal experience with industry or manufacturing	2.33	2	0.63	Other characteristic	Synthetic
Prior robotics training	2.20	2	0.65	Skill	Synthetic
Ability to complete repetitive or routine tasks	1.82	2	0.64	Ability	General
Ability to memorize lots of information	1.65	2	0.60	Ability	General
Scientific research	1.53	1	0.58	Skill	Analytical
Proficiency in artificial intelligence concepts and applications	1.47	1	0.58	Skill	Analytical

N = 45

After further breaking the list into quartiles based on importance scores, a tiered set of attributes can be determined. The top tier consists of those that are general and difficult to teach or credential. Based on their high average scores—all nearly "3" indicating the highest level of importance—and small standard deviations, these three characteristics and abilities were judged to be very important by almost all respondents. This finding is similar to Weaver's and Osterman's (2017) finding that among manufacturers, basic skills—and especially communication—are most highly demanded. However, the high ranking of mechanical aptitude suggests that integrators are also looking for an ability that is directly applicable to their work—in the way that a graphic design firm may equally value aesthetic aptitude.

The second tier is similar to the first, but contains only one "basic" ability—creativity—and three skills or other characteristics highly associated with a synthetic knowledge base. The high importance of "mechanical aptitude," "interest in working with hands," and "interest in 'tinkering' with things" suggests that the most successful integrators are oriented towards learning through tactile experience and physical experimentation with artifacts.

Tier 3 attributes, which should still be understood as generally "somewhat important," contain a mix of skills, like computer programming and prior robotics training, other characteristics, and abilities.

The most revealing result of the survey lies in the difference between the first and last two tiers. Only one of the top seven attributes most strongly associated with successful integrator employees is something that can be taught and credentialed in an educational institution. The other six can certainly be encouraged through schooling, but in considering a resume for an integrator position, one would have to look for indirect clues based on activities, interests, or classes taken to arrive at an initial evaluation of the degree to which a candidate possesses these attributes.

Other skills associated with the “creative” or “knowledge” economy such as computer programming and even prior robotics training fall into the third tier. While these skills are still seen as somewhat important by respondents—coursework and certifications in these areas could certainly give a candidate an advantage—they are of less relative importance than the abilities and other characteristics in the first two tiers. Robotics training itself ranks tenth out of the 14 total attributes.

This suggests that to the extent that there is in fact a skills gap or shortage in robotics systems integration, it might more accurately be called an “ability and other characteristics gap,” since these are the attributes that are more predictive of eventual success as integrator employees.

Finally, the two skills most strongly associated with analytical rather than synthetic robotics work—“scientific research” and “proficiency with AI concepts and applications”—are as expected not important to robotics systems integrators. It is somewhat surprising that they rank below “ability to complete repetitive or routine tasks” and “ability to memorize lots of information” since these were added mainly as “attention checks” to ensure that survey takers were thoughtfully completing the survey (Huang, Liu, & Bowling, 2015; Kung, Kwok, & Brown, 2018; Maniaci & Rogge, 2014). This suggests that the human capital needs of robotics systems integration are to a large extent distinct from those of robotics research and development.

7.6. Discussion of Human Capital in Robotics Systems Integration: Understanding the Synthetic Sensibility

In summary, synthetic knowledge does appear to be dominant in robotics systems integration. Drawing from answers to the questions posed in the survey and in interviews, synthetic knowledge (i.e. designing and constructing physical robotics automation systems) is more important than analytical knowledge (designing and creating robots themselves and the artificial intelligence concepts that power them). However, it should be kept in mind that the list of questions asked in this project is not exhaustive, so some analytical knowledge functions may not have been examined.

Nevertheless, integrators rely heavily on technical skill and labor (Research sub-Question 2a), with approximately a quarter of the industry's workforce engaged in skilled technical labor. Although integrators prefer to recruit engineers with bachelor's degrees for entry-level openings, they also recruit heavily from local, non-four-year educational institutions (Research sub-Question 2b). Experienced integrator employees are rare and command high salaries because integrator-specific formal and informal training primarily happens on-the-job (Research sub-Question 2c).

The fact that integrators prioritize abilities and characteristics like interest in solving new problems, mechanical aptitude, communications skills, and interest in working with hands over more formal types of skills and knowledge (Research sub-Question 2d) is related to these human resources practices. While integration does involve a set of codified skills and knowledge, the people most successful at applying these skills and knowledge come to the profession with a background of tangible problem solving.

Finally, where formally codified skills and knowledge specifically related to robotics are concerned, proficiency with artificial intelligence concepts and applications—analytical knowledge that is typically acquired through advanced training at a university—ranks overall as the least important attribute out of the 14 listed on the survey. Training in the use of robots ranks much higher (Research sub-Question 2e).

For integrators, being able to configure and program a robot to work in a production system is distinct from and more important than having a fundamental understanding of how the artificial intelligence algorithms that drive the robot's functionality. This is (imperfectly) analogous to a pilot not needing to know exactly how a plane was designed in order to fly it. Similarly, robot designers (and aeronautical engineers) do not need to know exactly how robots (and planes) are used in order to create them.

This is not to say that it does not help to have familiarity with both the creation and use of the product for all parties along the supply chain. Certainly those designing industrial robots benefit from knowing how they are used, and integrators can use them more effectively if they understand the principles that enable their functionality. However, it is not likely an efficient allocation of resources for individuals, firms, or society to invest in redundant specialized knowledge along all segments of the robotics supply chain. While a bachelor's degree in any of several engineering subfields is sufficient for those pursuing integration careers, those who have invested in specialized master's or doctoral degrees will likely pursue more lucrative employment designing robotics and other devices with artificial intelligence capabilities.

This distinction between knowledge bases and skills along the robotics supply chain is important to keep in mind when considering workforce responses to the diffusion of robots and AI. Workforce and economic development strategies are often crafted around specific types of knowledge (Garmise, 2006) or products, as in the trend of "sectoral strategies" built around key manufacturing or service subsectors (Conway, 2014). These strategies make practical sense because they impose clear and easily definable boundaries. One could envision the creation of a "robotics corridor," with a university robotics engineering program connected to a business incubator or accelerator aimed at generating new robotics companies. However, it is unlikely that any American region will become a global leader in the design and development of industrial robots, as the U.S. ceded its competitive advantage in this field to Europe and Asia decades ago (see Chapter 5). Additionally, from a workforce perspective, a robotics corridor focused on research and development may only have limited opportunities for people without advanced degrees.

Any of these traditional strategies are in the mode of what Garmise (2006) calls "knowledge development" which

> "centers on two interrelated strategies: investing in new knowledge production (stimulating research, technology transfer, and restructuring business and workplace organizations) and investing in human capital development (skills, education, and workforce systems)" (p. 5).

The knowledge development approach is thus an outgrowth of and suffers from the same shortcoming as the MaHC approach to human capital, which is a preoccupation with identifiable and measurable areas of knowledge and skill.

More than discrete parcels of skill or knowledge, integrators look for a *sensibility*, which, borrowing from the knowledge base literature, I call a *synthetic sensibility*. The synthetic sensibility entails more than a collection of skills. Integrators are looking for people who confront physical, material, and spatial problems with an attitude of curiosity and interest. The top half of the list of ranked KSAOs identified in the survey (Table 7.6), such as interest in solving new problems, creativity, communication skills, interest in working with hands, and mechanical aptitude, are emblematic of this sensibility. Because the list of KSAOs on the questionnaire may have omitted skills that integrators would rate as highly important, the survey lacks sufficient information to claim that these abilities and other characteristics are *more* important than specific skills. But it does suggest that the possession of pre-existing synthetic qualities is highly important and a strong predictor of success in integration.

The practice of recruiting for a synthetic sensibility has several spatial implications. Since integrators do tend to recruit entry-level employees locally (recall the emphasis on nearby universities, community, and technical colleges in Section 7.4.2), they look for this sensibility in its local form. For example, two integrators located in small cities surrounded by rural areas both emphasized that they have success in hiring people who grew up in farming communities. One of these interviewees in the West North Central census division (see Figure 4.1 for map), explained:

> "It's good to have someone who has that farm kid mentality, right? They grew up in a way where they go, 'Oh, this thing was broken, but I fixed it…And I fixed it like this because it's not like I could go buy a new one. I had to fix this.' So, people who can look at something and say, 'Yeah, that might not be quite right. Let me tinker with that, and I'll get it right.' So, to be able to have that conceptual ability to look at a problem, I'll say, and find a solution…You can't read that on a resume, you have to have the conversation with them…"

Another integrator in a rural area of the South Atlantic census division said similarly,

> "…maybe why you see a lot of success in manufacturing in the South is our agricultural background. We've talked about it [internally in the firm]. If we could only hire from one sub-group of people, who would it be? And it would be farm kids because they know how to problem-solve, they know how to fix things on the fly… And they know that they've got to do it and they've got to do it fast because the cows still need to be milked everyday…the fields need to be plowed. So, they've got that work ethic, they've got that, 'Yes, we can. I don't know how we can yet but yes, we can.'"

This interviewee also added that her firm has hired people with degrees in areas as diverse as marine biology, forestry, and marketing (the latter to do programming). Several other interviewees noted that even in candidates with engineering degrees, they identify a synthetic sensibility through involvement in curricular or extra-curricular projects. For example, an East North Central census division integrator said:

> "If you give me a stack of 50 résumés that are mechanical engineering students, I'm going to sort through and see which ones participated in some sort of extracurricular program, whether it's a Formula car, or Baja car, or human-powered submarine, or Formula One car or something like that. Or they work on cars just in their own spare time. Something like that that gives me some tangible experience for them outside of their educational background."

To put these practices in perspective, it should be noted that integrators still do look for traditional indicators of entry-level human capital, such as a bachelor's degree, preferably in engineering. To some extent, they are simply looking for well-rounded, curious people—not an uncommon sentiment among people making hiring decisions.

Another reason integrators may not emphasize credentials associated with robotics systems integration work is because integration-related credentials are so rare at the entry level. As one integrator explained, "you can't really hire a robotics integrator from anywhere," meaning that there is no academic program that specifically prepares one for this work. Integrators are forced to look for potential rather than previous achievements. Despite the overall trend of a decline in employer-sponsored training (Cappelli, 2012), integrators have internalized and accepted the need for it. While several integrators expressed the need for more team-based, project-based, and practical training in university engineering programs (as opposed to the theoretical training that they claim dominates curricula), they did not advocate for specific additions to curricula when prompted.

As mentioned in Section 7.4, this problem manifests most consequentially in the search for mid- or senior-level staff. Because of the rarity of and amount of resources invested in these employees, there is steep competition for them, and they demand premium wages. Integrators thus make significant efforts to retain seasoned employees, often as they report in interviews, through cultivating close-knit and supportive organizational cultures. Although spatial solutions to the seasoned employee shortage do not appear common, one integrator reported being strategically located between two mid-size cities so that employees could be recruited and commute from either labor market.

The industry of robotics systems integration and the labor markets in which it is concentrated could thus benefit from several workforce interventions, specifically applicable to legacy industrial regions. The first is simply to offer more training in industrial automation applications. Although low- and medium-tech firms like integrators already commonly provide workers with significant on-the-job training opportunities (Corbett, 2008), increased community offerings in specific industrial automation applications could lighten the burden of integrators and related firms in providing on-the-job training and increase the overall labor supply for hard-to-fill industrial expertise. This need—and the potential of filling it on a regional basis—has been recognized in several places. For example, the state of Alabama built a dedicated robotics training center to provide free trainings to employees of Alabama firms, as well as offerings for some community college students in related programs (Leigh & Kraft, 2017b). Also, in the heart of one of the integrator industry's most prominent areas of geographic concentration, north-central Ohio, a school called Ramtec was established to provide training in robotics and related automation skills to local firms as well as high school and technical college students (Ramtec, 2019).

More fundamentally, and what this research suggests may be more impactful for legacy industrial regions with concentrations of integrators and related industries, is not a concrete policy recommendation, but rather a shift in thinking about the human capital necessary to produce the material resources needed to sustain and improve our quality of life. This shift constitutes a move away from the supposed placeless and culturally-agnostic paradigm of Fordist (or modernist) production and toward a recognition of places' industrial and material inheritances and their usefulness (Eisenburger, Doussard, Wolf-Powers, Schrock, & Marotta, 2019; Gibson, 2016). In Fordist logic, production can be moved anywhere in the world, where interchangeable parts and people can be inserted into systems to get them up and running. In practice, this was never entirely true, as workers devised unique "hacks" and local industrial cultures sprung up (see Gibson's [2016] study of bootmaking in El Paso, TX) within and despite mass production regimes.

In many cases, these inheritances, regardless of whether they have to do with agricultural or extractive industries or manufacturing, are aligned with synthetic sensibilities, because they involve solving material problems. Integrators recognize this in their recruiting practices, but this recognition could be expanded and formalized, especially in legacy industrial regions.

This is the thrust of various strands of literature, such as the Phoenix industries or Reindustrialization described in Chapter 1, "Material Inheritances" (Carr & Gibson, 2016), which advocates for recognizing inherited material skills as important to solving contemporary environmental challenges, and "Sustainable Transitions," (Truffer & Coenen, 2012) which advocates for turning existing industries into sustainable ones through regional structural transformation. An example of the latter is a project to transition a Swedish region dependent on forestry into a center of more sustainable biorefining activity (Coenen, Moodysson, & Martin, 2015). However, there are few examples of this approach in general, and none reported in the U.S. These are all evolutionary in their outlook because they strongly depend on history and paths.

CHAPTER 8: CONCLUSIONS AND IMPLICATIONS FOR REGIONAL ECONOMIC EVOLUTION

8.1. Summary of Research

Having recounted results and interpretations of the survey and interview research on robotics systems integrators and their role in regional economic evolution, we can now answer the three main research questions established at the outset, and discuss their implications for economic development planning at the local and regional level. Recall from Chapter 3, the research questions are:

1. **Are robotics integrators relational agents, and do they introduce related variety along the dimensions of**
    a. **Industry**
    b. **Technology**
    c. **Human capital (knowledge bases), and**
    d. **The supply chain?**
2. **Is a synthetic knowledge base dominant in the robotics systems integration industry, and if so, how does it show up in integrator human capital practices (research sub-questions 2a – 2e)?**
3. **Do integrators increase the capacity of local manufacturing clusters to be adaptively resilient?**

The first question and its sub-questions can be answered in the affirmative. Robotics systems integrators' unique position in the supply chain enables them to be relational agents, introducing variety to local and regional economies, as well as recirculating and enhancing it. They do this along several dimensions. They span the technological spectrum from high- to low- tech industrial robotics applications by working with well-established and cutting-edge robotics technologies and industrial applications (sections 6.3 and 6.4). Similarly, they serve customers that are both technologically sophisticated and technologically lagging (section 6.6). They further serve customers that compete on the basis of quality, exclusivity, and distinction, as well as those that compete on cost (section 6.6). The list of industries they serve is itself expansive (section 6.5), suggesting that techniques they develop for food manufacturers, for example, may be applicable to metal manufacturers. This cross-sectoral injection of innovative capacity is important to help local clusters avoid lock-in resulting from excessive inward looking routines.

Most importantly, most integration projects are occasions for learning, and integrators frequently transfer this information and know-how to their customers (sections 5.2 and 5.3). This transfer is accomplished either indirectly through the systems they build and install, or directly, by equipping customers with new knowledge (and sometimes curiosity and interest) about how to maintain, operate, and improve their systems.

Several qualifications to these findings deserve mention. First, while robotics systems integrators work with almost all manufacturing subsectors, their penetration into nondurable sectors like chemicals and petroleum remains low. This lack of contact is partly due to technological and cost constraints, because robots are often not appropriate for nondurable production processes (although most integrators can also design non-robotics automation systems), and because some nondurable industries operate on narrow margins that preclude investments in sophisticated automation systems. Thus, related variety transfer remains much lower between integrators and nondurable manufacturers than it does between integrators and durable manufacturers, which may preclude certain types of learning and evolution.

The findings of this dissertation contribute to evolutionary economic geography theory by empirically demonstrating the role of agency in transferring related variety. The case of integrators shows how agents capture knowledge of robotics technology—generally originating from outside a US region—reconfigure it to solve specific production problems in a region, and in many cases help to embed that knowledge within their own organizations and manufacturers in the region. Moreover, it illustrates the mechanisms for this transfer as well as the specific points within a supply chain and innovation system where the transfer takes place. For example, integrators introduce a new technology to a customer on more than half of their projects (Table 5.1), and integrators' work often results in a "champion of the machine," or a customer's employee who becomes skilled and invested in the system designed by the integrator, thereby increasing the robotics knowledge of the manufacturer.

These findings reinforce accumulated evidence that prior experience with manufacturing technology is one of the strongest predictors of future technological upgrading in manufacturing (Astebro, 2002; Gómez & Vargas, 2012; Helper, 1995; Stoneman & Kwon, 1994). This positive feedback dynamic strongly suggests that integrators have the potential to increase the capacity for adaptive resilience of regional manufacturing communities if their efforts can be focused on potential local customers currently outside of integrator networks.

Being able to accomplish such increased local concentration would require further exploration of knowledge intensive business services (KIBS), and technologically oriented KIBS (t-KIBS) in particular. Robotics systems integrators are one small example of t-KIBS, and others can be expected to work in similar, but certainly not identical, ways. For example, there are engineering services providers in the construction, energy production, and extractive industries, and although the innovation practices of each type of t-KIBS may be subject to industrial and regional idiosyncracies, there may be generalities that can be drawn to support these firms and their supply chains.

8.2. Synthetic Sensibility as Human Capital in Regional Economic Evolution

The standard view of human capital among social scientists and policy makers is insufficient to describe the human capital needs of robotics system integrators. While knowledge and skills are valued in potential entry-level employees, integrators' criteria for assessing knowledge and skills are not uniform or easily quantifiable. Depending on the position, a bachelor's degree is not required, and in some cases, even engineering positions in integrator firms do not require bachelor's degrees in an engineering discipline (section 7.3b). Rather, integrators indicate that they look for personal attributes and characteristics that lend themselves to systems integration work. These include interest in and comfort with solving novel, often tangible problems (section 7.3f). These attributes, combined with continued investment in training and on-the-job experience make seasoned integrators extremely valuable human capital assets, and leave them in short supply (section 7.3c).

Borrowing from the knowledge base framework, this paper has used the term "synthetic sensibility" to describe the collection of attributes and characteristics comprising the personnel profile desired by integrators. In robotics systems integration, and likely in other similar industries, the synthetic sensibility should be seen as complementary rather than inferior to the more traditionally sought after analytical indicators of advanced degrees in specific fields.

8.3. Implications for Regions, Industries, and Future Research

The results from this research are not sufficient to establish a causal link between integrators and the adaptive resilience of local manufacturing clusters. However, when viewed in conjunction with related research on EEG, KIBS, and the geography of human capital, the evidence compiled on robotics systems integrators strongly suggests that the type of work they perform can enhance the adaptive capacity of local manufacturing clusters, especially in legacy industrial regions.

While it has previously been theorized and confirmed to some extent on a quantitative level that continued infusions of related variety can help to sustain the competitiveness of regions, the mechanisms through which this variety becomes embedded in and transmitted through an economy have been unclear. Looking closely at robotics systems integrators has highlighted several possible pathways along which this phenomenon may occur. They include 1) configuring general purpose robotics innovations from outside of a region to solve specific problems within the region, 2) embedding this knowledge and experience within both the integrator firms to be applied to other projects and the customer firm to enable sustained productivity growth and facilitate continued technological upgrading, and 3) leveraging (often latent) synthetic sensibilities in workers to complement more traditional knowledge- and skill-based human capital.

Integrators are of course a small group and likely not influential enough by themselves to recalibrate the evolutionary path of a stagnating or declining region or manufacturing cluster. Integrators tend to be regionally-rooted, with most still being located in the places in which they were founded. But these roots appear to be loosening as manufacturing continues its geographic trajectory of globalization and decentralization. Further research is needed to determine the extent to which integrators are similar to other types of t-KIBS, as well as the industrial customers they serve (including manufacturers, energy producers, builders, distributors, and agricultural product producers).

This research would be part of a multi-pronged approach to determine the causal impact of t-KIBS on a regional manufacturing cluster or a regional economy more generally. The qualitative portion would involve more thoroughly exploring the impact of integrators along both ends of the supply chain by collecting more data from robot suppliers and integrator customers. This research should also extend to similar types of technical and industrial service providers such as those in the energy and agricultural industries, following cues from Weis and Bonvillian's (2013) assessment of lagging innovation in these industries.

The quantitative portion of this research program would first need to establish a taxonomy of t-KIBS in the U.S. context that is 1) cohesive, meaning that businesses are grouped according to their role in absorbing and transmitting related variety throughout an industrial ecosystem, and 2) encompassing a group large enough that its growth or decline could reasonably be expected to impact a regional economy. Since the Scientific, Professional, and Technical Services NAICS sector is poorly disambiguated, this effort would likely require manual classification from a proprietary business database. Brenner et al. (2018) provide a thoughtful starting point using European business data and dividing KIBS broadly into financial and non-financial categories. Despite this limitation, they carefully recognize that the effects of changes in the KIBS sector may not be immediate—and in fact may initially cause a reduction in manufacturing employment due to an infusion of labor saving processes—and also may be subject to various types of positive and negative feedback loops that condition results over time.

While regional employment growth, both in the manufacturing sector and overall, is for practical purposes the ultimate outcome of interest, employment may not be the best indicator of adaptive resilience since as Brenner et al. (2018) note, KIBS may not have a consistently positive effect on employment. Thus, it may be useful to assess regional manufacturing output or productivity as a dependent variable to gauge robustness.

Because as this research has shown, integrators also are increasingly likely to export their services to other regions, it may be that growth in technical services providers are economic development ends in themselves. Consistent with other research on KIBS and their role in the knowledge economy, integrators capture an outsized portion of value: according to what integrators report, two thirds of the total cost of industrial robotics systems are embedded in integrators' knowledge (see section 3.3.3d). On one hand, this situation reinforces the findings from skill-biased technological change literature, which is that the gains made by those whose work is complemented by technology come at the expense of those whose work is replaced (Autor, Levy, & Murnane, 2003; Liu & Grusky, 2013). Robotics systems integrators concede that customers' goals are often, but certainly not always, to reduce labor costs by implementing technology.

On the other hand, integrators' work frequently results in freeing incumbent workers from mundane work and allowing them to engage in higher value-added and at least anecdotally more fulfilling work (this is almost exclusively the case in tight labor markets, which characterizes the period when this research took place). The most desirable outcome of such "upskilling" is when customers' employees become "champions of the machine" that integrators have designed and installed. This moment of knowledge transfer is literally related variety at work at the micro level to propel regional economic evolution.

Unlike traditional interpretations of skill biased technological change, where analysts and managers are the "winners," the case of the integrator exposes openings for people with a "synthetic sensibility," or facility with technical and mechanical problem solving to participate in the knowledge economy. Rather than assuming this sensibility to have been rendered obsolete by credentializable skills and knowledge, places where the synthetic sensibility lingers through heritage can enlist it to build a more adaptive and resilient economy.

Additionally, despite integrators' prioritization of the synthetic sensibility and general willingness to tolerate the lack of a talent pipeline with specific industrial automation and robotics skills, further credentializable training pathways for this type of knowledge would help integration and other industries by reducing the amount they need to invest in human capital.

While more research into synthetic knowledge-dominant industries and their contributions to regional economic evolution is warranted, these findings related to robotics systems integrators suggest that industrial legacies are rich in related variety and can be incorporated into the creation of new regional economic trajectories.

APPENDIX: Selected T-tests, F-Tests, and Interpretations

- ENC = East North Central Census Division
- All tests assess integrators in ENC division against those in all other divisions combined.
- F-tests are included when t-test hypothesis is accepted.

1. Percent of customers within 4.5 hour drive

Null hypothesis accepted: No difference between ENC and non-ENC groups

Descriptive Statistics				
VAR	*Sample size*	*Mean*	*Standard Deviation*	*Variance*
Not ENC	16	48.875	30.13719	908.25
ENC	19	61.05263	25.52662	651.60819
t-test assuming equal variances (homoscedastic)				
Degrees of Freedom	33			
Hypothesized Mean Difference	0			
Pooled Variance	768.26356			
Test Statistics	1.29482			
Two-tailed distribution				
p-level	0.20437	*Critical Value (5%)*	2.03452	

2. Average project cost

Null hypothesis accepted: No difference between ENC and non-ENC groups

Descriptive Statistics				
Variable	*Sample size*	*Mean*	*Standard Deviation*	*Variance*
Not ENC	21	6	1.04881	1.1
ENC	20	5.75	1.48235	2.19737
t-test assuming equal variances (homoscedastic)				
Degrees of Freedom	39			
Hypothesized Mean Difference	0			
Pooled Variance	1.63462			
Test Statistics	0.62584			
Two-tailed distribution				
p-level	0.53506	*Critical Value (5%)*	2.02269	

3. Highest project cost

Null hypothesis accepted: No difference between ENC and non-ENC groups

Descriptive Statistics				
Variable	*Sample size*	*Mean*	*Standard Deviation*	*Variance*
Not ENC	20	2,891,142	3,498,602.34888	1.22402E+13
ENC	21	4,517,285	6,656,507.9219	4.43091E+13
t-test assuming equal variances (homoscedastic)				
Degrees of Freedom	39			
Hypothesized Mean Difference	0			
Pooled Variance	2.86858E+13			
Test Statistics	0.97176			
Two-tailed distribution				
p-level	0.33716	*Critical Value (5%)*	2.02269	

4. Perceived concentration of knowledge in region relative to others in North America

Null hypothesis rejected and f-test indicates equal variances. ENC integrators perceive there to be more industrial robotics knowledge in their own region than integrators in other regions do.

Descriptive Statistics				
Variable	*Sample size*	*Mean*	*Standard Deviation*	*Variance*
Not ENC	23	3.26087	1.38883	1.92885
ENC	21	4.42857	1.07571	1.15714
t-test assuming equal variances (homoscedastic)				
Degrees of Freedom	42			
Hypothesized Mean Difference	0			
Pooled Variance	1.56137			
Test Statistics	3.09618			
Two-tailed distribution				
p-level	0.00349	*Critical Value (5%)*	2.01808	

F-test	1.66691	F Critical value (5%)	2.1016	

p-level 1-tailed	0.12757	p-level 2-tailed	0.25513	
H0 (5%)?	*accepted*			

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